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**THE EFFECTS OF TRUNK MUSCLE FATIGUE AND LOAD TIMING ON SPINE
MECHANICS DURING SUDDEN HAND LOADING**

By

Diane Eva Grondin

A Thesis

**Submitted to the Faculty of Graduate Studies and Research
through Human Kinetics
in Partial Fulfillment of the Requirements for
the Degree of Masters of Human Kinetics at the
University of Windsor**

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2003

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ABSTRACT

Sudden loading of the trunk, especially when it is unexpected, leads to higher muscle forces. Muscle fatigue, on the other hand, decreases the force producing capacity of muscles. The current experiment provides insight into the control of spine mechanics during trunk muscle fatigue in a situation of sudden loading that affects spinal stability.

Fifteen females received a sudden load in the hands, at a time that could be anticipated and at a time that could not. Participants received these loading trials (a) while rested, (b) with back muscle fatigue, and (c) with a combination of back and abdominal muscle fatigue. Measures were taken from the EMG activity from four trunk muscles (LES, TES, EO and IO), and from the Trunk Angle and CoP data. A 3 X 2 Repeated Measures ANOVA was performed to determine the effects of trunk muscle fatigue and load timing on the preparations made prior to the load impact, and on the responses that followed.

Results showed there were no preparations made prior to the perturbation when it could be anticipated. The Peak Responses following the perturbation were greater in the unexpected versus the expected condition. Therefore, preparations must have taken place prior to the anticipated perturbations, perhaps in other segments of the body. An increase in the trunk muscle fatigue led to an increase in the Baseline activity of the trunk muscles, but had no effect on the Peak Responses of the trunk muscles. Hence, the increased activation with fatigue was somewhat successful in decreasing the effect of the perturbation. Also, there was increased activation of both (opposing) muscle groups when only one muscle group was fatigued. This is evidence of cocontraction and supports the concept of spinal stability.

DEDICATION

**This paper is dedicated to my parents, David and Lorraine Grondin, as they dedicate their
time and energy to their children every day of their life.**

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LIST OF ABBREVIATIONS

APA	anticipatory postural adjustment
CNS	central nervous system
CoP	centre of pressure
EMG	electromyography
GRF	ground reaction force
LBP	low back pain
MPF	mean power frequency
MVC	maximum voluntary contraction
NEMG	normalized electromyography

Independent Variables:

F_0 , F_E , F_{EF} rested condition, fatigue of the trunk extensors, fatigue of the trunk extensors and flexors

T_K , T_R , S timing known, timing random, surprise condition

Muscles	TES	thoracic erector spinae
	LES	lumbar erector spinae
	IO	internal obliques
	EO	external obliques

Dependent Variables:

NEMG normalized EMG

TiPk time-to-peak

LIST OF DEFINITIONS

Anticipatory postural adjustment (APA): An adjustment in whole-body and/or segmental postures prior to a self-inflicted or external perturbation, so as to minimize the effects of the perturbation and to optimize coordination.

Centre of mass: The location used to represent where the centre of a system is located, according to the masses and positions of the body segments.

Centre of pressure (CoP): The location where the largest amount of pressure is situated, measured while standing on a force plate.

Cocontraction: The simultaneous contraction of opposing muscle groups to increase stiffness and minimize the effects of a perturbation.

Electromechanical delay: The time between the beginning of EMG activity and the onset of muscle force production (Häkkinen & Komi, 1983).

Fatigue: "An acute impairment of performance that includes both an increase in the perceived effort necessary to exert a desired force and an eventual inability to produce this force" (Enoka & Stuart, 1992, p. 1631).

Ground reaction force (GRF): The equal and opposite force of the ground, acting to oppose the body weight of a person in stance.

Latency: The time between the presentation of a reflex stimulus and the onset of EMG activity (Häkkinen & Komi, 1983). (*Also called "reaction time"*)

Motor program: A set of muscle commands that is set before a movement begins that allows the entire movement to be carried out without influence of peripheral feedback (Keele, 1968).

Reaction time: *See "Latency"*

Reflex: A stereotyped muscle reaction to a sensory stimulus (Sherrington, 1906 as cited in Shumway-Cook & Woollacott, 1995).

Response time: A general term used to describe the speed of response of a muscle following a stimulus. (Incorporates latency, electromechanical delay and TtPk).

Stability: The ability of the human system to return to its position of equilibrium following a small perturbation (Stokes, Gardner-Morse, Henry & Badger, 2000).

Time-to-Peak (TtPk): The duration between the onset of a stimulus and the time at which a given variable reaches its peak.

Chapter 1

INTRODUCTION

The occurrence of low back pain (LBP) is of major concern to ergonomists, engineers and industrial workers. The reasons behind the concern are the disabling consequences of back injuries, the high compensation costs, and, above all, the large number of cases. For instance, among select American industries, 26.5% of the injuries involving days off work are injuries to the back (Mital, Pennathur & Kansal, 1999). Furthermore, it was estimated that the direct and indirect costs of back injuries total \$50-100 billion per year (Frymoyer & Cats-Baril, 1991). As with other conditions such as osteoarthritis of the lower limbs, LBP is associated with a decreased quality of life. Sufferers report negative self-perceptions in terms of their physical capacities, mental health and pain (Guillemin, Virion, Escudier, de Talancé & Weryha, 2001).

The occurrence of LBP is often associated with certain clinical populations or with certain professions. For example, women who are obese in their early adulthood have an increased risk of developing back pain (Lake, Power & Cole, 2000). The risk increases by 47% for pain onset within the next 10 years, and by 78% for pain onset several years later (Lake et al., 2000). Moreover, age has been shown to be the primary risk factor in the occurrence of LBP and cervicobrachial and lumbosacral radicular syndromes (Kostova & Koleva, 2001). In the study by Kostova and Koleva (2001), gender was found to be a secondary risk factor, such that women were more prone to cervicobrachial and lumbosacral radicular syndromes than were men.

Furthermore, LBP is widespread among workers in manual labour professions. High muscle forces, high repetition and awkward postures constitute major risk factors

for these workers. Essentially, highly forceful and repetitive movements lead to muscle fatigue. Norman et al. (1998) found that the lumbar moment and the hand force accumulated over a shift were significant risk factors in the development of low back disease. Injury results when the demands of the job surpass the tolerance or the strength and endurance of the tissues (Mital & Kumar, 1998). The recent focus has been placed on the accumulation of low back stresses, over long periods of time, as indicators of risk (Norman et al., 1998). This, in turn, is connected to the cumulative effects of tissue fatigue.

Another major risk factor is sudden perturbations of the trunk. These perturbations can take the form of suddenly increasing or decreasing the amount of weight held in the hands, shifting weight, lifting a higher or lower weight than expected, accidentally dropping a load, and slips or falls. Perturbations such as these are often encountered by physiotherapists, nurses who lift patients, and drivers who load and unload trucks (Radebold, Cholewicki, Panjabi & Patel, 2000). Luggage dispatchers and refuse collectors also handle objects of unknown weight (Commissaris & Toussaint, 1997). In a study by Smedley, Egger, Cooper and Coggon (1997), 38% of the nurses who were free of back pain for at least one month experienced new LBP during the follow up (mean = 18.6 months). Apart from a history of LBP, which was the greatest predictor of new LBP, the nurses who reported frequent manual transfer, repositioning, or lifting of patients were at an increased risk. Magora (1973) found a positive relationship between the frequency of sudden maximal efforts, particularly of the unexpected nature, and the occurrence of LBP. Furthermore, Manning, Mitchell and Blanchfield (1984) found that 66% of the back injuries reported in an industrial setting were elicited by some form of underfoot mishap. Low back injuries caused by sudden exertions are less frequent than

injuries caused by material handling but, admittedly, they are more costly (Bigos et al., 1986).

Fatigue can lead to musculoskeletal injury by increasing the demands on the muscles. Prolonged or repeated muscle contractions lead to a decline in muscle force (Asmussen, 1979). However, fatigue also decreases the efficiency of the muscle in transforming muscle excitation into muscle force (Bigland-Ritchie, Jones & Woods, 1979). Consequently, during a sustained muscle contraction, the amplitude of the electromyography (EMG) must increase in order to maintain the desired force level (Petrofsky, Glaser, Phillips, Lind & Williams, 1982; Häkkinen & Komi, 1983; Kirsch & Rymer, 1987; Duchêne & Goubel, 1990).

Moreover, although one group of researchers found that back endurance was not a significant predictor of LBP (Gibbons, Videman and Battle, 1997), several researchers have shown that there is a strong correlation between isometric back endurance and LBP. For instance, Biering-Sørensen (1984) found that, among men, high back muscle endurance was associated with a low, first-time occurrence of LBP. Similarly, Hultman, Nordin, Saraste and Ohlsen (1993) found that the risk of belonging to a population of chronic and/or recurrent LBP increased with poor back endurance. Luoto, Heliovaara, Hurri and Alaranta (1995) also showed that the isometric back endurance test is the only physical capacity measurement that correlates significantly with a new occurrence of LBP for both genders. In addition, Nicolaisen and Jorgensen (1985) found that women who had LBP that prevented them from working had significantly lower endurance times than women who were free of LBP or who had LBP that did not prevent them from working. Therefore, the results of these studies suggest that poor back endurance or, rather, fatigue of the back extensors, may lead to LBP.

Moreover, proprioception may also be impaired with fatigue (Sharpe & Miles, 1993; Johnston, Howard, Cawley & Losse, 1998; Chabran, Maton & Fourment, 2002) as is motor control (Brereton & McGill, 1999). Some authors report that the reaction time (or muscle latency) increases with fatigue (Wilder et al., 1996), whereas others have found that it stays the same (Häkkinen & Komi, 1983) or actually decreases (Allison & Henry, 2002). Allison and Henry (2002) hypothesized that a decrease in muscle latency helps to compensate for a slower rate of force production that is associated with fatigue.

All these factors have implications during sudden perturbations. Several researchers have shown that fatigue has a negative effect on static balance (Nardone, Tarantola, Giordano & Schieppati, 1997; Johnston et al., 1998), on dynamic stability (Sparto, 1998), and on lifting kinematics (Sparto, 1998; van Dieën, van der Burg, Raaijmakers & Toussaint, 1998). For instance, van Dieën et al. (1998) found that repetitive lifting led to increasingly negative angular velocities (or more intense eccentric contractions) of the back, lumbosacral flexion nearing the elastic limit, and more twist. Fatigue may also lead to injury by impairing coordination, thereby leading to increased spinal instability or more frequent use of unnatural motions (Mital, Nicholson & Ayoub, 1993).

Sudden perturbations are hazardous by nature, but they are even more likely to cause injury when they are unexpected. If an individual is expecting a sudden load, he or she can prepare for the event to minimize trunk displacement, forces (Marras, Rangarajulu & Lavender, 1987) and muscle activity (Lavender et al., 1989; Lavender & Marras, 1995). These preparations take the form of anticipatory postural adjustments (APAs) (Oddsson & Thorstensson, 1986; Aruin & Latash, 1995; Lavender & Marras, 1995) and cocontraction of the trunk flexor and extensor muscle groups (Cresswell, Oddsson & Thorstensson, 1994; Thomas, Lavender, Corcos & Andersson, 1998;

Krajcarski, Potvin & Chiang, 1999; Stokes, Gardner-Morse, Henry & Badger, 2000). APAs are adjustments made in whole-body or segmental postures prior to self-inflicted or external perturbations, so as to minimize the effects of the perturbation and to optimize coordination. They are prepared by the central nervous system (CNS) and are based on the information made available to the person (Shiratori & Latash, 2001). Cocontraction, however, is the simultaneous contraction of opposing muscle groups to maximize stability and to minimize the effects of a perturbation. Stability, in this sense, is defined as the ability of the human system to return to its position of equilibrium following a small perturbation (Stokes et al., 2000).

In terms of APAs, displacements in the centre of foot pressure (CoP) and rotations of the hips and knees have been documented in anticipation of trunk perturbations (Oddsson & Thorstensson, 1986; Aruin & Latash, 1995). Thus, the trunk segment works in concert with the lower limbs in the control of posture during sudden trunk perturbations. Moreover, the large majority of researchers agree that cocontraction of the trunk muscles serves to stiffen the spine (Bergmark, 1989; Lavender, Marras & Miller, 1993; Cresswell et al., 1994; Cholewicki, Panjabi & Khachatryan, 1997; Gardner-Morse & Stokes, 1998; Granata & Marras, 2000) to minimize disturbances in the event of a perturbation.

Balance, proprioception, and muscle reaction time are all very important to control posture in the event of a sudden perturbation. Because fatigue has been shown to negatively affect these measures (Miles, 1993; Wilder et al., 1996; Nardone et al., 1997; Sharpe & Johnston et al., 1998), it is important to study the effects of fatigue during sudden perturbations of the trunk. Although fatigue can be challenging to test, it is an

important component to consider, as individuals experience at least some degree of fatigue throughout most of their eight-hour work shift.

To date, studies on fatigue and sudden loading have been limited. Parcero (2000) fatigued the back extensors and applied step-input loads to a variety of initial static pre-loads. Movement was restricted to the trunk and upper body, as the pelvis was restricted. Inconsistent effects of fatigue were found in the cocontraction data (prior to and during loading), although some interaction effects were found between fatigue level and pre-load level in terms of the maximum trunk angle elicited by the sudden loading. However, the scope of this study was limited to measures of the trunk in isolation of the CoP, and to back muscle fatigue in isolation of abdominal fatigue.

Granata, Orishimo and Sanford (2001) also assessed the effects of fatigue during sudden trunk perturbations. They asked subjects to hold a plastic crate in their hands and applied a sudden load equal to 2.5% of the subject's maximum lifting capacity, dropped from 0.5 m. Prior to each trial, participants were informed as to whether a sudden load would be applied. In trials where a sudden load was applied, it was applied after a random delay period within a 10-second window. Trials were performed in either a fatigued or unfatigued state. Granata et al. (2001) found that fatigue led to an increase in the trunk flexor and extensor coactivation, but that expectation of the sudden load did not. This second finding contradicts the results of other studies (Lavender et al., 1993; Cresswell et al., 1994; Thomas et al., 1998). Granata et al. (2001) hypothesized that the contradictory findings may have been due to the relatively low load weight in their experiment. For example, the load used by Granata et al. (2001) was equal to merely 25% of the impulse used by Thomas et al. (1998), and to only 35% of the load magnitude used by Lavender et al. (1993). However, again, the scope of the study by Granata et al.

(2001) was limited to measures of the trunk and to testing the effects of back muscle fatigue in isolation of abdominal fatigue.

Finally, Allison and Henry (2002) performed a pilot study to determine the effect of back muscle fatigue on the feed-forward muscle activity of abdominal muscles (internal obliques, external obliques and rectus abdominis) and the longissimus back muscle during rapid arm raising. A pulling motion was used to fatigue the subjects, which likely targeted the back muscles. Essentially, they found that there was a general decrease in the muscle latencies following fatigue, possibly to compensate for the decreased rate of force production associated with fatigue. However, only four individuals participated in this pilot study, and only temporal variables during the anticipatory stage of the sudden arm movement were measured. Also, this preliminary study was limited to measures of the trunk in isolation of the body's CoP, and only the effects of back muscle fatigue were examined.

To understand the control of spine mechanics during fatigue and sudden loading, it is important to consider the spine from a stability perspective by testing the agonist and antagonist muscles. However, previous research looking at fatigue during sudden loading has mainly focused on back extensor fatigue (Brereton & McGill, 1999; Parcero, 2000; Granata et al., 2001; Allison & Henry, 2002). Consequently, this research has been unable to determine how the system responds when the abdominal muscles are also fatigued. In addition, few researchers have tested the response of the trunk muscles in concert with the lower limbs during sudden perturbations (Haumann, 2002; Brown, Haumann and Potvin, in press). It is important to study the stabilizing function of the spine in conjunction with the balancing function of the lower limbs, as the trunk and the

lower limb segments are physically linked and do not operate in isolation (Oddsson & Thorstensson, 1986; Aruin & Latash, 1995).

Purpose

The current experiment further investigates the control of spine mechanics in the presence of back and abdominal muscle fatigue. Specifically, the goal is to better understand how the system adapts to changes that threaten spinal stability. To perturb the system, trunk muscle fatigue will be induced and then a sudden load will be applied. Although the focus of the current experiment is on the adaptations made by the spine as a result of fatigue and sudden loading, the control of balance, as measured by the whole-body response, will also be considered. The effects of muscle fatigue will be assessed by first fatiguing the back muscles and, second, by adding subsequent fatigue of the abdominal muscles. A load will be dropped into a bin held by the participants according to one of three load timing conditions: (a) at a time known by the subject, (b) at random times within a 10-second window, and (c) a surprise condition where subject thinks she knows the timing of the load.

Hypotheses

1. *APAs will be significantly greater in the known timing condition (T_K) than in the random timing condition (T_R).*

Aruin and Latash (1995) found that subjects displayed APAs (shifts in the CoP and small angular displacements of the hip and knee joints) when they were aware that unloading was about to occur. Lavender and Marras (1995) also found that subjects tended to posteriorly displace their centre of gravity in anticipation of sudden anterior loading, although the results were somewhat variable. Therefore, APAs are also expected to occur in anticipation of the sudden loading in the current experiment.

2. *The degree of cocontraction prior to the loading will be significantly higher in the known versus random timing condition.*

Several authors have found that cocontraction of the trunk muscles occurs in anticipation of a known perturbation (Marras et al., 1987; Lavender et al., 1989; Cresswell et al., 1994; Thomas et al., 1998; Krajcarski et al., 1999; Stokes et al., 2000), and so similar results are expected here.

3. *The peak responses and the response times of the muscles will be greater following the perturbation in the random versus the known timing condition.*

Anticipation of a sudden load has been shown to lead to lower muscle forces, slower rates of muscle activity onset (Marras et al., 1987; Lavender et al., 1989), and shorter durations of exertion (Marras et al., 1987) following the perturbation, compared to when a loading is unexpected.

4. *When the loading is anticipated (T_K), APAs will be lowest in the rested (F_0) condition, followed by the extensor fatigue condition (F_E) and then by the flexor-extensor fatigue condition (F_{EF}).*

Because speed of contraction (Bigland-Ritchie et al., 1979; Bigland-Ritchie, Johansson, Lippold & Woods, 1983; Häkkinen & Komi, 1983) and muscle force (Asmussen, 1979) decrease with fatigue, the body will adopt other methods to better prepare for the sudden load when it is expected under fatigued conditions. As a result, less demand will be imposed on the fatigued muscles immediately following the loading than if alternate APA strategies were not adopted.

5. *The degree of cocontraction prior to loading will be highest in the F_{EF} condition, followed by the F_E condition and then by the F_0 condition.*

Muscle fatigue has been shown to increase the degree of cocontraction during fatiguing, isometric, lateral bend exertions (Potvin & O'Brien, 1998). Also, cocontraction will increase to stiffen the spine, thereby decreasing the response required from the weakened and fatigued muscles immediately following the perturbation.

6. *The peak responses and the response times of the muscles following the loading will increase from the F_0 condition to the F_E condition, and again from the F_E condition to the F_{EF} condition.*

Because speed of contraction (Bigland-Ritchie et al., 1979; Bigland-Ritchie et al., 1983; Häkkinen & Komi, 1983) and muscle force (Asmussen, 1979) decrease with fatigue, the effects of the perturbation will be greater with fatigue, as the muscles will

be less capable of responding to the perturbation. Furthermore, the reaction time of the muscles (Wilder et al., 1996) as well as the electromechanical delay between the onset of EMG and the onset of muscle force has been shown to increase with fatigue (Häkkinen & Komi, 1983). Therefore, increases in the response times of the muscles are expected in the current experiment.

7. *Generally, the Surprise trials will show trends similar to the T_R trials, with minimal preparation (APAs and cocontraction) and, thus, greater effects immediately following the perturbation (greater peaks and times to peaks).*

Hypothetically, the 10-second window in the random condition is long enough so that the subjects will not prepare for the sudden load for the entire 10 seconds.

Conceivably, it would be energetically inefficient to do so. Similarly, during the Surprise condition, participants will plan to prepare for the sudden load just prior to it because they will think that they know the exact timing of the perturbation, as during the T_K condition. However, the sudden load will occur earlier than they had anticipated, and so they will be unprepared, as during the T_R condition.

Chapter 2

REVIEW OF LITERATURE

Localized Muscle Fatigue

Fatigue Defined

As defined by Enoka and Stuart (1992, p. 1631), “fatigue is a general concept intended to denote an acute impairment of performance that includes both an increase in the perceived effort necessary to exert a desired force and an eventual inability to produce this force”. Although there is no consensus on how fatigue should be defined, in this sense, fatigue is a continuous process (Asmussen, 1979) rather than a discrete event. Somewhere along the continuum lies the point where a person is no longer able to produce the *required* force, although he or she may still be able to produce a lesser force.

In addition, fatigue is task-dependent. Enoka and Stuart (1992) note that the type of task designates the underlying mechanism(s) and also the site(s) of fatigue. The type of fatigue that is of concern in the current experiment is localized muscle fatigue, as would be experienced during prolonged or repeated muscle contractions of a particular muscle group.

Sites of Fatigue

In a general sense, fatigue can be either central or peripheral in nature. Central fatigue is distinguished from peripheral fatigue as occurring proximal to the motor neurons (mainly in the brain), whereas peripheral fatigue occurs primarily within the motor units (i.e., the motor neurons, peripheral nerves, motor endplates and muscle fibres) (Asmussen, 1979).

Central fatigue is important to consider in the current experiment. For instance, motivation may play a role in central fatigue. A person may continue to perform a fatiguing exercise if he or she is highly motivated to do so. Endurance time depends not only on the fatigability of the muscle fibres, but also on factors such as the pain tolerance, competitiveness and boredom of the individual (Mannion & Dolan, 1994). Bigland-Ritchie, Cafarelli and Vøllestad (1986) point out that maintaining maximum CNS drive is demanding and unpleasant, and requires a great deal of motivation and practice. Furthermore, the ability to voluntarily maximally contract a muscle may also vary depending on the muscle that is being targeted (Bigland-Ritchie et al., 1986). For instance, in the case of the plantar flexor muscles, the CNS cannot provide the necessary drive for maximum contraction (Edwards, 1981).

Effects of Fatigue on Coordination

Some muscles or movements have synergistic muscles that may also be incorporated during the maximal voluntary contraction (MVC) (Duchêne & Goubel, 1990). The human body has a redundancy in the degrees of freedom due to the large number of joints and muscles that can be used to perform a task (Hadders-Algra & Forssberg, 1998). Gardner-Morse and Stokes (1998) point out that there are several redundant strategies that can be used to activate the muscles of the trunk in order to perform a specific task. To delay the onset of fatigue, the CNS may alter the neural strategy and recruit other muscles or motor units to provide the original muscles a period of rest throughout the contraction (Duchêne & Goubel, 1990). It is also believed that fatigue leads to a decrease in the coordination of muscle contractions, and, consequently, an increase in the use of unnatural muscle sequencing and movements (Mital et al., 1993;

Potvin & O'Brien, 1998). Note, as well, that unnatural or unaccustomed muscle sequencing would be especially likely to occur when the system is unexpectedly perturbed. *Figure 1* provides insight into the cyclic effects of fatigue during a repetitive lifting task.

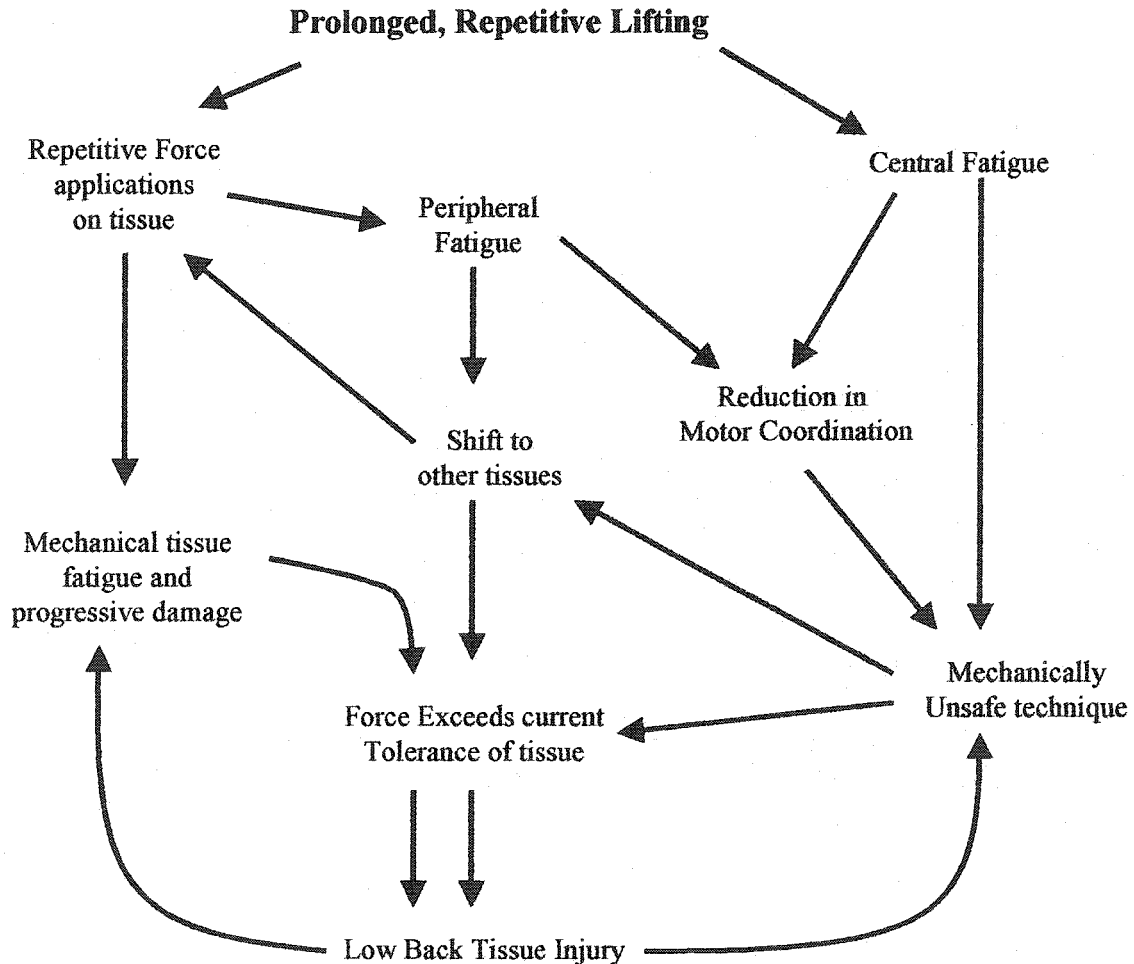


Figure 1. Flow chart of the cyclic effects of fatigue during a repetitive lifting task (Potvin, 1992). Essentially, repetitive lifting can lead to either peripheral or central fatigue. Repetitive force applications on the tissues leads to peripheral fatigue and tissue damage when the forces, either cumulative or acute, exceed the current tolerance of the tissues. Chronic fatigue leads to a reduction in coordination, which, in turn, may lead to unsafe lifting techniques. Chronic fatigue may also lead to a shift in the tissues that are used to perform a task, thereby predisposing these newly recruited tissues to acute trauma. Ultimately, the risk of a low back injury increases.

Moreover, Brereton and McGill (1999) also found that fatigue will, on occasion, produce improper muscle sequencing and movement patterns, and so injuries may result from random motor control errors. Yet, Brereton and McGill (1999) stated that motor control errors might be more common with fatigue if the system was more challenged, as during sudden perturbations. Although, van Dieën, Toussaint, Maurice and Mientjes (1996) found that, generally, the relative timing between joint rotations and the lumbosacral torque did not significantly change over a series of continuous, repetitive lifts, the authors hypothesized that a perturbation to the system might accentuate the changes in coordination. Thus, in a subsequent repetitive lifting experiment, van Dieën et al. (1998) had subjects release the load before lifting it again in order to perturb the system. Indeed, significant changes in coordination were found. Sparto (1998) also found that fatigue led to significant changes in the coordination and in the lifting kinematics of a repetitive lifting task.

Effects of Fatigue on EMG

Fatigue induces many changes in the action potentials and in the EMG of contracting muscles. Of interest in the current experiment are the fatigue-related changes in the amplitude of the EMG, in the conduction velocity of the action potentials, and the subsequent decreases in the frequency of the EMG power spectrum.

Amplitude of EMG

Fatigue induces a decrease in the maximum EMG activity and in the muscle force that can be produced. It has been shown that EMG declines by 50-70% during a MVC sustained for 60 seconds (Bigland-Ritchie et al., 1983). Yet, during sustained, submaximal contractions, EMG activity will actually increase whereas force will decrease (Petrofsky et al., 1982; Häkkinen & Komi, 1983; Kirsch & Rymer, 1987; Duchêne & Goubel, 1990). Häkkinen and Komi (1983) found that the integrated EMG increased significantly in the superficial knee extensor muscles when the contractile force was maintained. Furthermore, Petrofsky et al. (1982) found that the amplitude of the EMG rose in relation to the tension developed by the handgrip, biceps, adductor pollicis and quadriceps muscles (25, 40 or 70% MVC), and in relation to the degree of fatigue. Häkkinen and Komi (1983) also found that fatigue led to an increase in the EMG/force ratio. Thus, fatigue decreases the efficiency of the muscle in transforming muscle excitation into muscle force (Bigland-Ritchie et al., 1979).

Velocity of Action Potentials

During a muscle contraction, fatigue slows of the conduction velocity of the action potentials (Bigland-Ritchie et al., 1979; Bigland-Ritchie et al., 1983; Eberstein & Beattie, 1985). Bigland-Ritchie et al. (1983) also found that fatigue led to an increase in the twitch duration of a contraction, largely due to a slowed relaxation rate. Furthermore, this slowed velocity also serves to increase the area of the action potential (Bigland-Ritchie et al., 1979).

Shift of the EMG Power Spectrum to Lower Frequencies

Fatigue has a major effect on the EMG power spectrum. Specifically, there is a shift toward a lower mean power frequency, or an increase in the low frequency components and a concomitant decrease in the high frequency components of a signal (Petrofsky et al., 1982; Häkkinen & Komi, 1983; Kirsch & Rymer, 1987; Kuorinka, 1988; Duchêne & Goubel, 1990). In fact, the median and mean frequencies of the power spectrum are often used as measures of fatigue (Petrofsky et al., 1982) and have been shown to be quite reliable (Potvin & Norman, 1993). Mannion and Dolan (1994) found that the rate of decline in the median frequency was significantly related to back extensor isometric endurance time. However, they also noted that the rate of decline in the median frequency accounted for 50% of the variance in the time to fatigue, meaning that motivational factors were probably also largely involved. In terms of measuring fatigue, the EMG frequency spectrum is a better indicator of fatigue than is the EMG amplitude, as the EMG amplitude is affected by the muscle force (Petrofsky et al., 1982).

The most accepted reason for the decrease in the mean frequency is the slowed velocity of the action potentials associated with fatigue. It is believed that the shape of action potentials may change and become longer in duration (slowed velocity), thereby decreasing the high frequency content of the power spectrum (Mills, 1982; Häkkinen & Komi, 1983; Kranz, Williams, Cassell, Caddy & Silberstein, 1983; Mayer, Kondraske, Mooney, Carmichael & Butsch, 1989).

Recovery from Fatigue

The mechanisms and time-lines of recovery from localized muscular fatigue are especially important in experimental protocols. To test the effects of fatigue, one must ensure that a given level of fatigue is maintained or, rather, that a given level of recovery is not reached in the middle of a test trial. This is critical given the transient nature of fatigue (Asmussen, 1979).

Recovery of the EMG Signal

The EMG signal recovers quite rapidly following a fatiguing contraction. Kuorinka (1988) found that the restitution of the power spectrum frequency occurred very quickly following a fatiguing exercise. This restitution began to return to the starting value at 2-5 minutes following the point of exhaustion. However, Kuorinka (1988) points out that the mechanical and physiological recovery of a muscle takes much longer. Kirsch and Rymer (1987) also found that the fatigue-related changes in the EMG spectrum recovered rather quickly, but that the muscle weakness, evidenced by the positive shift in the EMG-torque relationship, was substantial and lasted longer than seven hours. Moreover, Häkkinen and Komi (1983) found that force recovered almost fully within three minutes following a 50% MVC continuous isometric fatiguing contraction, but that the EMG amplitude showed minimal recovery. The ratio of EMG to force, however, recovered very little, indicating a continued failure in the contractile process (Häkkinen & Komi, 1983).

Furthermore, Jonsson (1978) stated that the recovery from fatigue depends on the nature and on the type of exercise that has been performed (i.e., long duration exercise may lead to long recovery times), and also on the fatigue variable that is being measured.

Kuorinka (1988) also stated that neither the muscle power (% MVC) used to fatigue the subjects nor the type of exercise (static versus kinetic exercise) generally makes a difference on the curves and on the times of recovery, as long as the point of exhaustion has been reached. However, different muscles have different compositions of fast twitch versus slow twitch muscle fibres, and so different muscles or even different fibres within a muscle may reach exhaustion at various times (Häkkinen & Komi, 1983).

Posture and Balance

Balance is especially challenging for humans, as humans are bipedal locomotors with high centres of mass and relatively small bases of support. Balance becomes even more challenging when variables such as fatigue or sudden perturbations come into the equation. The trunk segment occupies approximately 50% of the body's mass, and so movements of the trunk, especially quick ones, have a large impact on balance (Oddsson & Thorstensson, 1986).

Leg Versus Trunk Strategies to Control Posture

The control of balance can occur at the level of the ankles, knees, hips and/or trunk. Anticipation of a perturbation can affect the positioning of the joints and segments of the body in order to minimize the postural disturbance and the likelihood of balance loss. These attempts to re-position the body prior to a perturbation are termed "APAs", and can be reflected as changes in the CoP to put the centre of mass in an optimal location. For example, in anticipation of a sudden anterior load, one may slightly extend the trunk to shift the centre of mass backward. This shift in the system's centre of mass

can be measured as changes in the location of the ground reaction force (GRF) or CoP at the feet.

Anticipatory Postural Adjustments

In most manual handling situations, humans are able to anticipate the weight of the load to be handled and to activate their muscles appropriately, so as to maintain stability of the system and to adequately handle the object. Prior to performing voluntary arm movements, changes in muscle activation and posture occur in the trunk and lower limbs to aid in stability, control and coordination. Specifically, posture is adjusted by shifting the centre of mass backward (Commissaris & Toussaint, 1997; van Dieën & de Looze, 1999) and by cocontracting the flexor and extensor muscle groups to stiffen the joints (Cresswell et al., 1994).

APAs not only occur with voluntary arm movements, but also prior to rapid trunk flexions (Oddsson & Thorstensson, 1986). For instance, early during trunk flexions, the knees bend and then the ankles extend (Oddsson & Thorstensson, 1986). Lavender and Marras (1995) found that, although the results were somewhat variable, subjects tended to posteriorly displace their centre of gravity in anticipation of a sudden anterior load. However, Haumann (2002) found that participants shifted their CoP anteriorly prior to an expected symmetrical loading of the trunk applied through the hands.

Essentially, these APAs progress in a feed-forward manner to minimize balance disturbances (Cresswell et al., 1994). Complications and disruptions occur, however, when the perturbation is unexpected and the system is unable to anticipate the disturbance (Cresswell et al., 1994). Compensatory reactions (those initiated by sensory feedback) would, in such a case, take on a larger role (Latash, 1998).

Proprioceptors

The proprioceptive reflex system also plays a role in the control of posture. Through this system (as well as through the visual and vestibular systems) the body is able to detect unexpected events or disruptions in the motor program (Dietz, 1992). Proprioceptors are specialized cells that convey information about the position of the body in space, the relative position of body segments (joint angles) and the length and tension of muscles (Kandel & Schwartz, 1985; Latash, 1998; Bear, Connors & Paradiso, 2001). Muscle spindles and Golgi tendon organs are types of proprioceptors. Muscle spindles are sensitive to changes in muscle length and velocity, whereas Golgi tendon organs are sensitive to changes in force. Proprioceptors react by altering their rate of firing that, in turn, leads to a change in the length of a muscle (Latash, 1998) and an adjustment of posture.

Allum, Honegger and Acuna (as cited in Allum, Bloem, Carpenter, Hulliger & Hadders-Algra, 1998) stated that vestibulo-spinal and proprioceptive inputs from the knee and trunk are involved in triggering balance corrections. Specifically, in terms of proprioceptive inputs, the timing of corrections is likely triggered by knee flexion and/or trunk rotation relative to the pelvis (Allum, Honegger et al. as cited in Allum et al., 1998). In a study by Bloem, Allum, Carpenter and Honegger (1998), forward flexion of the trunk occurred prior to activation of the paraspinal muscles. Therefore, the authors inferred that the trunk movement was a trigger for the postural adaptations in the paraspinal muscles.

Motor Programs

One way the CNS is able to control posture is through central programming (Dietz, 1992). A motor program was defined by Keele (1968) as a programmed response that is set before a movement begins that allows the entire movement to be carried out without influence of peripheral feedback. Motor programs are innate (Dietz, 1992) and are based on past experiences (Brooks, 1979). Note, however, that motor programs can be altered if, (a) the individual is given prior instruction on how to respond or, (b) when unexpected events occur (the program is interrupted) (Dietz, 1992). For example, the motor program used to go down a flight of stairs is interrupted when a person is not watching the stairs and expects one last step, when really he or she has already reached the bottom (Dietz, 1992). Preprogramming is the *process* of preparing the motor program for initiation (Schmidt & Lee, 1999) and is performed prior to movement initiation.

Voluntary Versus Reflexive Movements

Voluntary movements are consciously controlled by the individual. During feed-forward voluntary movements, the signal for a movement is supplied "*ahead of time*" and readies the system for either (a) an upcoming motor command or, (b) the receipt of particular feedback information (Schmidt & Lee, 1999). Conversely, during feedback-controlled movements, the controller *changes* command signals according to the sensory information made available from the outcome of the movement, allowing for corrective actions (Shumway-Cook & Woollacott, 1995; Fox, 1996; Latash, 1998). Although the feedback loop allows for corrections, this is done at the cost of speed, and slower reactions can be detrimental when an individual is suddenly perturbed (Latash, 1998). Negative feedback is information that inhibits (diminishes or corrects for) the original

response to an external force (Fox, 1996; Latash, 1998). Negative feedback loops are apparent in situations of sudden perturbations, as they allow the human body to minimize the effects of an external perturbation (Latash, 1998).

Conversely, Sherrington first defined the reflex in 1906 as a stereotyped muscle reaction to a sensory stimulus (as cited in Shumway-Cook & Woollacott, 1995). Reflexes occur involuntarily. Specifically, a T-reflex (or tendon reflex) occurs when the muscle is quickly stretched, leading to an increase in firing from the primary endings of muscle spindles (Shumway-Cook & Woollacott, 1995; Fox, 1996; Latash, 1998).

Thus, in situations of sudden perturbations, there is a feed-forward mechanism prepared in advance by the CNS that can be executed prior to the perturbation in the form of APAs, or after the perturbation as a result of a trigger (i.e., the sudden load). The initial response following the perturbation is reflexive in nature and is not only a function of the feed-forward mechanism, but also a function of the reflexive feedback information that is supplied by the muscle spindles and Golgi tendon organs.

Effects of Fatigue on Reflexes

Although, generally speaking, fatigue has been shown to increase the response time of muscles, its effect on the reaction time and on the electromechanical delay of a muscle may differ. The reaction time (or muscle latency) is the time between the presentation of the reflex stimulus and EMG onset, whereas the electromechanical delay is the time between the beginning of EMG activity and the beginning of muscle force production (Häkkinen & Komi, 1983). Wilder et al. (1996) found that when fatigue of the erector spinae muscles was induced by vibration, the reaction time of these muscles increased. However, others have shown that muscle latencies decrease (Allison and Henry, 2002) or

stay the same (Häkkinen and Komi, 1983) with fatigue. In addition, Häkkinen and Komi (1983) found that the electromechanical delay increases with fatigue, likely due to a failure in the muscle contraction process, namely the slowed conduction velocity of the action potentials.

Effects of Fatigue on Balance

Balance may be affected by fatigue because of proprioceptive inhibition, or, in cases of severe fatigue, because the muscles are so fatigued that they are unable to generate enough force to maintain balance (Johnston et al., 1998). Yet, in most circumstances of fatigue, the former reason is more probable (Johnston et al., 1998; Chabran et al., 2002). Muscle fatigue inhibits the neuromuscular feedback system acting at the joint (Johnston et al., 1998). Fatigue also inhibits both the afferent and efferent signals in the neuromuscular loop of the knee (Johnston et al., 1998). It has been documented that most anterior cruciate ligament injuries occur at the end of a sporting event when individuals are fatigued. For example, in recreational skiing, particularly, anterior cruciate ligament ruptures often occur at the end of the day (Feagin et al., 1987). In addition, Sharpe and Miles (1993) stated that central fatigue leads to changes in elbow position sense, possibly due to proprioceptive impairment.

Fatigue also negatively affects balance. Following a closed kinetic chain antagonistic exercise (similar to a stair stepper), Johnston et al. (1998) found that fatigue significantly decreased balance during three static balancing tests. Furthermore, Sparto (1998) found that fatigue led to a nearly significant decrease in postural stability in the anterior-posterior direction, as measured during a long-lasting repetitive lifting task. Nardone et

al. (1997) also found that the sway area and the sway path significantly increased following a treadmill fatiguing session.

Sudden Loading of the Trunk

Mechanisms of Injury

During manual handling, the trunk is particularly vulnerable to overexertion compared to other segments of the body. The extensor muscles of the back have a much shorter moment arm than an external load supported by the hands, thereby putting the back muscles at a mechanical disadvantage. This disadvantage must be overcome by exerting more extensor muscle force (Lavender et al., 1989). However, the situation becomes even more complicated when an externally applied load suddenly perturbs the trunk. Peak muscle forces in the trunk are much greater in sudden loading than in static conditions, and even more so when sudden loading is unexpected (Marras et al., 1987; Lavender et al., 1989; Lavender et al., 1993). According to Lavender et al. (1993), excessive muscle force is required to maintain stability during sudden unexpected loading because, (a) loading in itself is dynamic in nature, and (b) a startle response occurs during unexpected loading, whereby the system over-reacts. These demand higher muscle forces, which are linked to an increased risk of low back injury. Andersson (1981) found, through epidemiological studies, that workers who were subjected to unexpected loadings were particularly susceptible to low back injury.

Additionally, when the muscles of the trunk are not provided sufficient time to prepare for a perturbation, they may initially undergo a lengthening (eccentric) contraction immediately following the perturbation (Carlson, Nilsson, Thorstensson &

Zomlefer, 1981). During an eccentric contraction, the contractile force is less than the resistance force, leading to increased muscle fibre damage. The sudden load may also cause rapid flexion of the spine and an especially large forward bending moment (Mannion, Adams & Dolan, 2000), which has been associated with LBP. Greater extensor moment is required from the back muscles to counteract the large flexor moment. This flexion of the spine is thought to occur because the back extensors are “slow” postural muscles (Mannion et al., 1997) and have poor reaction time in response to suddenly applied loads.

Spinal Stability Through Cocontraction

Generally, cocontraction of the trunk muscles (simultaneous contraction of the agonist (extensor) and antagonist (flexor) muscle groups) helps stabilize the spine but at a cost of higher energy expenditure and increased compression on the spine. The agonist muscles are the primary movers and are the most active, whereas the antagonist muscles oppose the primary movers. Cocontraction removes “slack” from the system, leading to a quicker and stiffer response following perturbations (Lavender et al., 1993). Skeletal muscle stiffness is also proportional to the muscle force (Gardner-Morse & Stokes, 1998; Cholewicki, Juluru & McGill, 1999). Hughes, Bean and Chaffin (1995) predict that, as the abdominal muscles cocontract, the compressive force is up to 5.5 times higher than the force increase in the abdominal muscles. Also, Granata and Marras (2000) found that the spinal load increased by 12-18% when they added antagonistic muscle activity to their model. Conversely, spinal stability increased by 36-64% with the addition of the antagonistic activity (Granata & Marras, 2000). The improvement in stability was, therefore, significantly greater than the increase in spinal load (Granata & Marras, 2000).

Several authors state that the role of cocontraction is to stabilize the spine against potential perturbations (i.e., Bergmark, 1989; Cholewicki et al., 1997; Gardner-Morse & Stokes, 1998), and that the anticipatory coactivation of the trunk muscles prior to a sudden perturbation is an example of a feed-forward mechanism (Marras et al., 1987; Lavender et al., 1989). Gardner-Morse and Stokes (1998) conclude that, without any active muscle stiffness, the spine would buckle (even when in a position of equilibrium). Active muscles act as stabilizing springs, such that active responses to small disturbances are often not required (Gardner-Morse & Stokes, 1998).

Conversely, Lavender et al. (1993) reported an inconsistent coactivation of the antagonist muscles across subjects in preparation for sudden loading, although the erector spinae muscles were consistently active. Furthermore, Gardner-Morse and Stokes (1998) predict that increased levels of coactivation in the abdominal muscles (from 0-6%) led to increased stability. There were some drawbacks to the coactivation, however. These included a significant increase in muscle fatigue rate and a small increase in spinal compression. Note, however, that increased compression on a joint also produces increased joint stiffness, which contributes to stability. Cholewicki and McGill (1996) state that too much compression leads to an increased risk of tissue damage, but, also, that too little compression makes the spine unstable, also leading to an increased risk of injury. Hence, somewhere in the middle there is an optimal level of compression, and the risk of injury is lowest (Cholewicki & McGill, 1996).

Moreover, muscle fatigue affects the degree of cocontraction. With fatigue, activation of both the agonist and antagonist muscle groups increases so that the cocontraction forces are also increased (Potvin & O'Brien, 1998). Potvin and O'Brien (1998) also found that, as fatigue progressively increased, the force became more

variable, meaning that there was a decreased ability to coordinate the trunk muscle contractions. The amplitudes of the agonist and antagonist EMG signals also became more variable, perhaps because the body was attempting to alternate between muscles to provide certain muscles a period of rest (Potvin & O'Brien, 1998).

Expected Versus Unexpected Trunk Perturbations

The body is able to compensate for unexpected perturbations at several levels. First, there is the peripheral elasticity of the muscles, tendons and other tissues. During joint displacement, this elasticity provides instantaneous resistance against the joint movement (Latash, 1998). Second, there is the stretch reflex, which also has elastic properties and dampens the perturbation at the latency of a reflex (Latash, 1998). The third level involves preprogrammed corrective reactions, or muscle activation patterns (Latash, 1998). These corrective reactions can occur as quickly as 100 ms following the perturbation, and so they are preprogrammed rather than voluntary (Latash, 1998). These reactions may be general (i.e., cocontraction of agonist and antagonist muscle groups to increase stiffness) or specific to the direction of the perturbation (Latash, 1998).

Theoretically, there can be a much lower risk of injury if a perturbation is expected rather than unexpected. If a person is able to anticipate the timing of a sudden load, the motor system may be able to coordinate and scale the muscle forces accordingly so that excessive force is not exerted and so that the system responds efficiently. Likewise, anticipation of a loading allows the body to stabilize itself prior to the perturbation so as to minimize trunk displacement. To maintain trunk equilibrium, the trunk must be activated prior to the perturbation, given that the mechanical delay of the trunk muscles is more than 100 ms (van Dieën & de Looze, 1999).

Effects of Expectation on the Preparations Made Prior to the Perturbation

One would expect that there would be increased muscle activity *prior* to a sudden load if the participant were able to expect the sudden load. This idea has held true for many studies (Lavender & Marras, 1995; Thomas et al., 1998; Shiratori & Latash, 2001; Haumann, 2002). In their experiment, Thomas et al. (1998) loaded a harness worn by participants, and it was found that the erector spinae and external oblique muscles were active prior to the loading, leading to decreased trunk displacement following the perturbation.

Moreover, Lavender and Marras (1995) found that when a warning signal was provided to subjects prior to a sudden load, the pre-load erector spinae muscle activity significantly increased, as did the activity of the latissimus dorsi, although the magnitudes of the muscle torques were very small. However, consistent trends were not found in the muscle torques of the rectus abdominis and external oblique muscles, or in the trunk flexion (trunk stiffness) data, as measured by the lumbar motion monitor during the sudden loading stage.

In a study by Shiratori and Latash (2001), anticipation of a sudden load led to changes in the background EMG activity of the participants. Specifically, the background EMG activity of the arm, trunk and leg muscles changed when the sudden load was anticipated and was induced by both the experimenter and the participant. Furthermore, these preparations were seen when the load was dropped from all the heights, with the exception of the zero height, which did not allow for anticipation. As the release height increased, the preparations started earlier in the experimenter-release condition, and they were of greater magnitude in both the experimenter- and the self-release conditions. The

magnitudes of the preparatory EMG also increased for the heavier loads, although the timing of these preparations did not change as a function of load weight.

Haumann (2002) also found that the some of the agonist muscles (thoracic and lumbar erector spinae) and also the antagonists (external and internal obliques) increased their activation just prior to sudden trunk loading, which was received by the upper limbs. This occurred when participants were able to anticipate the perturbation.

Additionally, Krajcarski et al. (1999) compared conditions of different pre-load magnitudes and different load magnitudes, such that the final load was the same (4%+24% of maximum extensor moment versus 16%+12% of maximum extensor moment). It was hypothesized that a higher pre-load load would lead to greater spine stiffness (Krajcarski et al., 1999). This hypothesis held true. Results showed that the condition where the higher load was added (4%+24%) produced greater initial trunk acceleration into flexion than did the 16%+12% condition. Thus, the former condition required larger extensor muscle moments and higher abdominal activity to compensate for the lower initial stiffness (Krajcarski et al., 1999). Stokes et al. (2000) also found that increased preactivation of the trunk muscles leads to a smaller muscle reaction following a perturbation. Increases in the trunk stiffness decrease the trunk displacement and the peak muscle activity (Thomas et al., 1998) immediately following the perturbation.

The belief that the muscles contract in preparation for an expected perturbation did not, however, hold true for Granata et al. (2001). These authors found no significant changes in the muscle activity in preparation for a sudden load. An explanation for their unusual finding was that Granata et al. (2001) used a much lighter weight than that used by other researchers (Lavender et al., 1993; Thomas et al., 1998). Or, possibly, the “expected” trials were actually somewhat unexpected in nature, as the loading occurred at

random times within a 10-second window. Participants knew that the loading would occur, but had up to 10 s to wait before the loading. Consequently, perhaps extensive preparatory cocontraction did not occur because it would have been energetically inefficient to hold contractions for up to 10 s while waiting for the load.

Effects of Expectation on the Response Following the Perturbation

Marras et al. (1987) sought to determine whether unexpected loading was associated with excessive trunk forces following a perturbation and what the magnitude of these overcompensations would be. They stated that a system could over-respond in three ways: First, by increasing the magnitude of exertion (greater peak and mean forces), second, by increasing the rate of muscle force onset, and third, by increasing the duration of exertion, all of which put greater stresses on the tissues of the spine. Their results showed that sudden loading produced an increase in the mean force 2.7 times greater in the unexpected condition versus the expected condition. As well, the increase in the peak force was on average 1.7 times greater in the unexpected condition versus the expected condition, and greater rates of force onset were also observed in the unexpected trials. Finally, the duration of the muscle force exertion also increased by an average of 12% in the unexpected condition. Thus, the authors concluded that the muscles responded to the same degree in the unexpected condition as they would in the expected condition with double the weight.

Furthermore, Lavender et al. (1989) manipulated the length of warning time before loading. They concluded that longer preview times were associated with lower EMG amplitudes, lower rates of muscle activity onset and longer lead times of muscles. They defined "lead time" as the time between the elevated EMG and when the weight hit

the box, indicative of the anticipation of the loading. More warning was, therefore, associated with a decreased risk of low back injury. They also found that a preview time of at least 200 ms is preferred.

In a study done by Haumann (2002), the peak EMG values for all the muscles (except for the thoracic erector spinae) were significantly higher in the random load timing condition than in the expected load timing condition. This increase in the peak EMG was even more evident during “surprise” loading, when participants falsely believed that they knew when the loading would occur. Also, the participants’ CoP displaced anteriorly to a greater degree following the unexpected loadings versus the expected loadings, and even more so during the surprise trials. Therefore, the increased activation of the back, abdominal and leg muscles led to a greater change in the CoP measured at the feet.

Effects of Fatigue on the Muscle Activations During Sudden Perturbations

Few studies have been done to test the effects of fatigue on the muscle activations during sudden trunk perturbations. Parcero (2000) fatigued the back extensors and applied step-input loads to a variety of initial static pre-loads. Movement was restricted to the trunk and upper body, as the pelvis position was restricted. Inconsistent effects of fatigue were found in the pre-load data, although some interaction effects were found between the fatigue and pre-load level in terms of the maximum trunk angle.

Granata et al. (2001) also tested the effects of low back fatigue during sudden expected trunk loading. They found that fatigue was linked to an increase in the mean preparatory EMG amplitudes in the abdominal and back extensor muscles (cocontraction). The authors hypothesized that the body sought to compensate for the

force loss associated with fatigue by increasing trunk stiffness (Granata et al., 2001). Hence, the force loss experienced due to fatigue has the potential to compromise trunk stability.

Chapter 3

METHODS

Subjects

Fifteen healthy, female subjects were recruited for the experiment from the university population. Their mean (SD) height (m), mass (kg) and age (yrs) were 1.63 (0.06), 61.9 (7.5), and 22.3 (1.4), respectively. Females were recruited for the study because previous authors studying sudden loading have seldom tested female participants. All subjects were asked about their recent and current state of musculoskeletal health. Anyone who reported experiencing injuries of the low back or upper limbs, either currently or within the past six months, was excluded from the study. Also, it was requested that participants not perform any type of strength training exercise during the two days prior to their scheduled testing session. Only females who are right-handed were allowed to participate in the experiment. This was done in order to minimize any potential effects that side dominance may have had on the results, as EMG data was collected from only the right side of the body.

Ethical Considerations

There was a small risk of injury to the low back due to the sudden loading protocol used in conjunction with the muscular fatigue. However, sudden, unexpected loadings, similar to the ones in the current experiment, have been performed many times previously (Marras et al., 1987; Lavender et al., 1989; Lavender & Marras, 1995) and in conjunction with back muscle fatigue (Parcero, 2000; Granata et al., 2001). Nevertheless,

efforts were made to minimize the risk of injury to the participants. For instance, volunteers were only allowed to participate if they reported an absence of current or recent back pain or upper limb pain. "Recent" pain was defined as having occurred within the last six months. The experimenter also recommended stretching exercises following the test trials to minimize any muscle stiffness. Participants were properly secured in the hyperextension and abdominal benches during the fatiguing protocol. In addition, a chair was placed in front of the hyperextension bench so that the participants could immediately support their upper body weight once they had reached exhaustion. The experimenter also supervised the participants at all times. The MVCs were performed under very safe conditions and with confirmation that the subject was only supposed to contract to levels that she felt were safe for her.

All subjects gave informed consent prior to participation (*Appendix A*). The identity of the participants was kept confidential, and the results of the experiment were stored in secure computers in the Ergonomics and Biomechanics Laboratories. Participants were also allowed to withdraw from the experiment at any time. The study was reviewed and approved by the Research Ethics Board at the University of Windsor prior to commencement of the study.

Apparatus

Subjects stood on a force platform (Advanced Mechanical Technology Inc., AMTI), holding a lightweight plastic bin directly in front of their body. The bin weighed 0.3 kg and measured 30 cm wide. Subjects comfortably gripped the handles on either side of the bin, with their arms slightly outstretched. Participants were encouraged to hold the bin in a manner that was comfortable for them, with their elbows rotated to

approximately 45° so that the bin was situated low enough to load the low back. They were also instructed to ensure that the bin did not rest against their abdomen during the loading trials, and that their arms remained fairly stiff so that the momentum of the load was only minimally absorbed by the distal segments. Subjects were asked to look directly forward at all times, and to try to maintain a state of equilibrium by righting themselves back to their original position as quickly as possible following the loading perturbation. They were instructed to firmly grip the handles of the bin so that the bin did not fall. However, a table was placed just under the bin in the event that the bin was accidentally released from the hands.

An overhead pulley system was installed with a steel cable running through it. A load was attached to one end of the cable, and a handle was attached to the other. The cable and the load were positioned such that the load would drop directly into the centre of the hand-held bin. A target was drawn in the centre of the bin to ensure that the load would land in the centre of the bin. The load had a mass of 5 kg, which was heavy enough to elicit slight trunk flexion, shifting in the CoP, and increased trunk muscle activity. However, the load was light enough so that the subjects did not have to take a step to maintain balance.

The sudden load was applied without visual cues to the participant, as a black curtain hung between the bin and the subject's line of view. Furthermore, the pulley system was silent so that it did not provide auditory cues. The experimenter stood on the other side of the curtain and grasped the handle on the opposite end of the cable. Prior to each loading, the experimenter ensured that the weight was lifted 2.5 cm from the bottom of the bin. This way, the loading was sudden, but not ballistic in nature. A rubber band, equal to 2.5 cm in length, was attached vertically to the bottom of the load, such that

when the rubber band rested against the bottom of the bin, it was known that the proper loading height had been reached. *Figure 2* provides a diagram of the experimental apparatus.

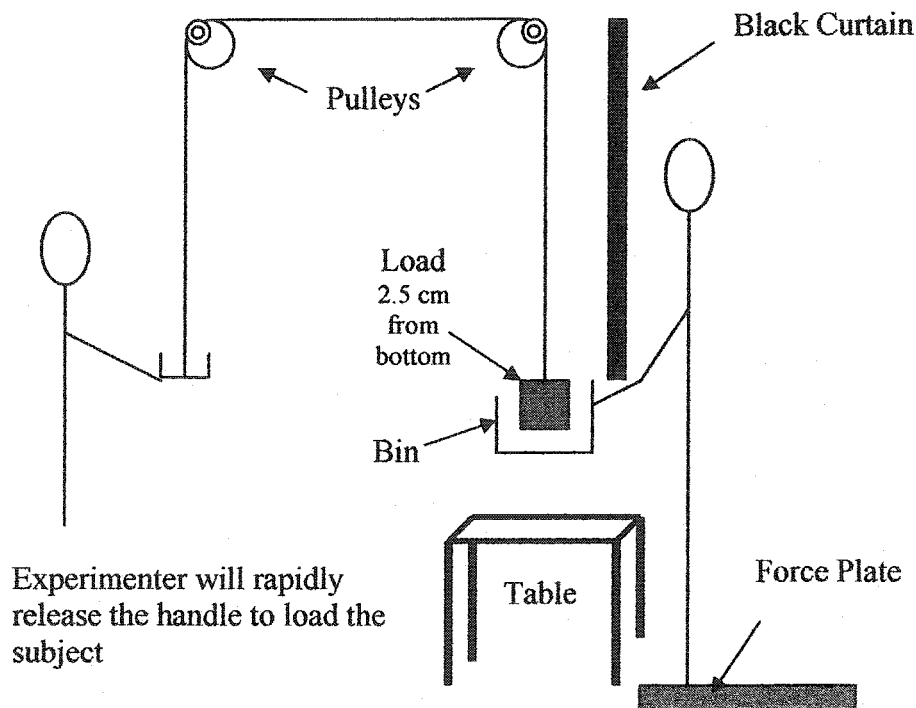


Figure 2. Diagram of the experimental apparatus. The experimenter applied the sudden load by quickly releasing the handle so that the weight dropped a distance of 2.5 cm into the bin, which was held by the participant. The load, applied into the hands of the participant, created a sudden anterior loading of the trunk, and increased the GRF, as measured by the force plate.

Data Collection

Prior to testing, each subject stood, forward-facing on the force plate, first in quiet stance and then while holding the bin with the load. The difference in the GRF magnitudes between the quiet stance and while holding the load was used to set the trigger for the computer program. This trigger would tell the computer program when the sudden loading had occurred, and when to start collecting data during the test trials. The location of stance on the force plate was such that the load fell directly into the bin, and the subject adopted a base of support that was comfortable for her. Once this posture was adopted, two pieces of tape were placed on the force platform at the tips of the toes of the participant, and the subject was required to stand in this location for the remainder of the test trials.

EMG

EMG was collected from four trunk muscles on the right side of the body: thoracic erector spinae (TES), lumbar erector spinae (LES), external obliques (EO), and internal obliques (IO). Bilateral symmetry was assumed. The reasons for this assumption were three-fold. First, the loading was always applied in the centre of the bin (as indicated by the target drawn on the bottom of the bin). Second, participants were screened for upper limb or back disorders so that asymmetries between sides could be minimized in this respect. And, third, the subjects were all right-handed, which helped maximize consistency in the data. Pairs of Ag-AgCl bipolar electrodes (Meditrace disposable pellet ECG electrodes, Graphic Controls) were placed longitudinally over the muscle bellies, with an inter-electrode distance of 2.5 cm. The electrode placements were the same as those described by McGill (1991) for the LES, TES, EO and IO muscles. A reference

electrode was placed on the lateral part of the rib cage. Prior to attaching the electrodes, the skin was lightly abraded with a paper towel and cleaned using an alcohol swab. The EMG signals were amplified (1000-5000X), sampled at 1000 Hz, and then converted with a 12-bit A/D card (National Instruments, Austin Texas). The raw EMG data was rectified and dual low-pass filtered with a second order Butterworth filter, with a cut-off frequency of 3 Hz.

Mean power frequencies (MPFs) and EMG amplitudes of the back and abdominal muscles were computed during the fatiguing intervals to help confirm that the muscle groups were, indeed, fatigued. Although a decrease of at least 10% in the MPF has been used as the criterion for fatigue (Potvin & Norman, 1993), the attainment of fatigue in the current experiment was defined as the point when the subject was no longer able to continue the fatiguing contractions in the required postures. The MPFs and the EMG amplitudes were recorded throughout the length of each fatiguing interval. The sample duration varied, as it was equal to the time it took for each participant to reach exhaustion for each fatiguing interval separately.

CoP

A force platform was used to measure the GRF in the vertical direction (F_z), and also the moment about the medial-lateral axis (M_x). The vertical GRF was used to determine the onset of loading and to calculate the CoP in the anterior-posterior direction (CoP_y), whereas M_x was only used to calculate the CoP.

$$CoP_y = M_x / F_z$$

The zero point for the CoP was recorded as the subject stood upright and still on the force plate. The force plate data was sampled at 1000 Hz, converted using the same 12-bit A/D card, synchronously with the EMG data, and then dual low-pass filtered with a second order Butterworth filter (cut-off frequency = 6 Hz).

Trunk Angular Displacement

To measure trunk angular displacement, a Penny & Giles goniometer (Biometrics Limited, DL 1001) was attached to the low back in a longitudinal manner, using two-sided tape. One end was attached over the sacrum, while the other end was placed over the lumbar region, directly on the spine. The Penny & Giles goniometer was used to measure the trunk angle as it outputs analog data that can be sampled at the same rate and put in sync with the EMG and CoP data. The zero point for the trunk angle was recorded as the subject stood upright and still. The trunk angle data was converted with the same 12-bit A/D card and synchronously with the other data, sampled at 1000 Hz, and dual low-pass filtered with a second order Butterworth filter (cut-off frequency = 3 Hz). All the data were recorded with LabView software (National Instruments) on a PC compatible computer.

MVC Collection

MVCs were collected from the four trunk muscles: TES, LES, IO and EO. For each muscle group, the subject was asked to gradually ramp up the force until she reached her absolute maximum, and then to hold it for 2-3 s. Each MVC was repeated twice to ensure that a valid MVC was obtained. Approximately 10 s of rest was allowed between MVC exertions.

For the TES and LES MVCs, participants were asked to lie prone on a padded table with their hands behind their head, and to extend their back as forcefully as possible, while the experimenter applied resistance to their shoulders. An assistant held down the legs of the participant to secure them while MVCs for the back muscles were being obtained. To get the MVC for the TES, participants were also asked to forcefully retract their scapulae in addition to extending backward at the back.

For the right IO and EO, participants lay supine on the padded table, with their knees flexed comfortably to approximately 90° . Participants were then asked to bend at the waist and to elevate their upper torso off the table by flexing their abdominal muscles. While flexed, they would then twist to 45° , first toward the right, then toward the left. The experimenter provided as much resistance as was necessary to get a maximum contraction from the participant. The resistance was applied to the shoulder of the participant in the opposite direction of the twist and, again, an assistant secured the subject's feet to the table.

For each muscle group, the largest filtered voltage obtained was denoted as the MVC amplitude for that particular muscle. All subsequent EMG signals were normalized according to the MVC amplitude (represented as 100%) for that subject. The MVC data was acquired and processed in the same manner as the EMG data, but with a cut-off frequency of 2 Hz, and then the EMG data was normalized to the MVC for each muscle.

Fatiguing Protocol

Extensor Fatigue

A horizontal back hyperextension bench was used to fatigue the back extensors. The bench was designed such that the participants lay prone. Their body weight was supported by two padded pieces on which their pelvis and shins rested. Therefore, their trunk and upper body were hanging off the bench, beginning with the superior border of the iliac crests. A chair was placed in front of the hyperextension bench so that the participants could support the weight of their torso on the back of the chair. *Figure 3a* provides a picture of a participant using the hyperextension bench.

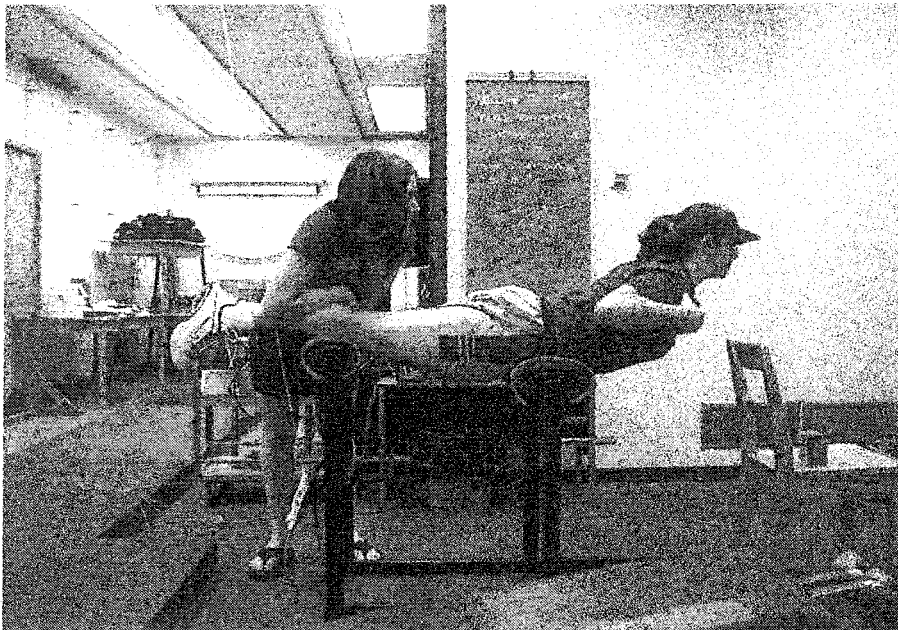


Figure 3a. A picture of the back extensor fatiguing protocol. The participant is anchored at the legs and extends at the back while holding a small weight (1.5 - 3.5 kg) in each hand. This isometric posture is held until exhaustion.

To fatigue the back muscles, participants were asked to put their arms up by their chest and to extend their back as far as they could, and to hold this isometric contraction until volitional fatigue or until they were unable to maintain even a horizontal posture.

Subjects were intermittently verbally encouraged to “keep going” to ensure that a high level of fatigue was attained. A similar method of fatigue has been used many times previously to measure back muscle endurance (Biering-Sørensen, 1984; Mayer et al., 1989; Mannion & Dolan, 1994). However, depending on the physical fitness of the individual, some participants were able to perform the exercise for a longer period of time. Therefore, to minimize boredom of the individual and the length of the testing interval, subjects who stated that they were physically fit held a weight in each hand (approximate weight = 1.5 - 3.5 kg) while their arms were placed up by their chest.

Once the subject claimed that she was exhausted, she was deemed to have had completed one set of back exercises. She was then given 30 s rest, followed by another set of exercises. During the rest period, participants leaned on the chair in front of them. See *Figure 4 (p. 47)* for the sequence of events during testing, that is, the order of the test trials and the fatiguing protocol.

Flexor Fatigue

Moreover, to fatigue the abdominal muscles, participants lay supine on an incline abdominal bench. Their feet hooked underneath two padded pieces of the bench, as indicated in *Figure 3b*.

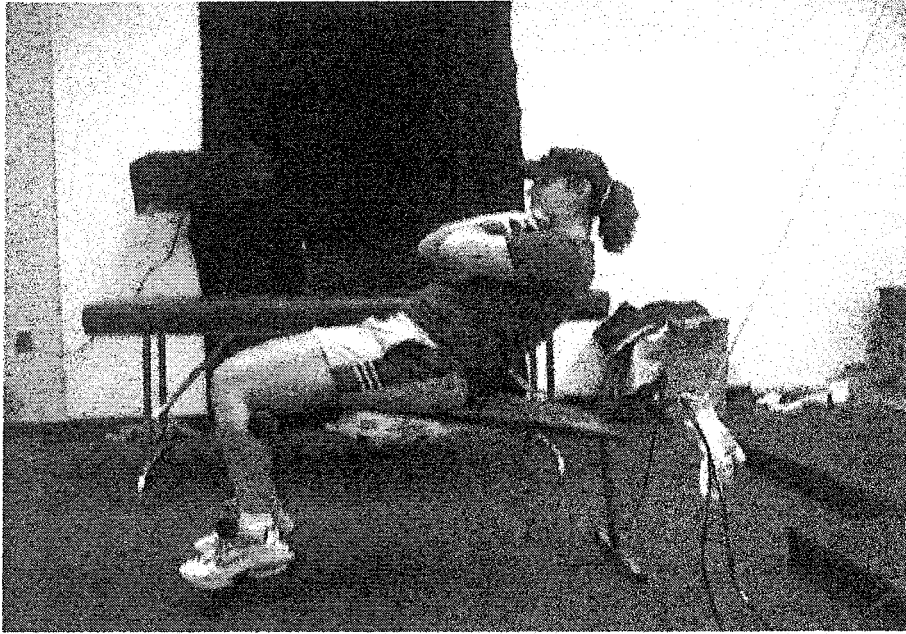


Figure 3b. A picture of the abdominal flexor fatiguing protocol. The participant is anchored at the knees and ankles and holds a small weight (1.5 – 3.5 kg) in each hand. She extends back and then “crunches” forward to approximately 45°. These “crunches” were performed while keeping the torso in the mid-sagittal plane, and then while twisting to both the right and left sides.

Subjects crossed their arms on their chest and “crunched” upward and forward to approximately 45° to the horizontal. They isometrically held this first contraction for 3 s before performing the subsequent abdominal crunches. This isometric contraction was necessary so that a reading of the initial EMG amplitude could be taken without the abdominal muscle lengths changing. As will be described later, the initial EMG amplitudes were compared to the final EMG amplitudes (post-fatigue) in order to help assess the degree of fatigue reached by the muscles. Muscle lengths must be consistent when using EMG amplitude to assess fatigue.

Following the first isometric contraction lasting 3 s, participants proceeded to extend backward toward the bench, and then to “crunch” forward again, first while looking straight ahead, and then while twisting toward one side and then toward the other.

The twisting motion was incorporated into the fatiguing routine in order to adequately recruit the oblique muscles. Participants repeated this sequence (“crunch” toward the centre, “crunch” toward one side, and “crunch” toward the other side) until volitional fatigue, extending backward toward the bench between each contraction. Again, verbal encouragement was given to maximize the degree of fatigue. Also, subjects who stated that they were physically fit were given the option of holding a weight in each hand (approximate weight = 1.5 - 3.5 kg), which rested on their chest. Finally, once the subject said that she could no longer perform the fatiguing exercise, she performed one last isometric contraction while facing forward. Again, she held this contraction for a duration of 3 s, while flexed to 45°. This provided the final EMG amplitude value to compare to the initial value, as explained above. Because this final value was recorded in a posture similar to the first one, it could be used to assess the degree of fatigue that had been reached.

Furthermore, the participant was given either 30 s rest, followed by another set of exercises, or was asked to perform the loading trials, depending on which fatiguing interval the subject had just completed (*Figure 4, p. 47*). During the rest period, the participants remained in a seated position on the abdominal bench. Note that several fatiguing intervals were performed to ensure that the subjects were substantially fatigued. Also, for the fatigue conditions (F_E and F_{EF}), exercises were performed in between each block of loading trials to minimize the amount of recovery. However, to prevent the occurrence fatigue between the two blocks of trials in the F_0 condition, 1 minute of rest was allowed. Moreover, because the final fatigue condition involved concurrent abdominal and erector spinae fatigue, both the back and abdominal fatiguing intervals were performed prior to the loading trials for this condition.

To minimize the duration and, thus, the amount of recovery between the end of the fatiguing interval and the block of loading trials, participants were anchored to the both the extensor and flexor exercise benches by the experimenter herself (*Figures 3a & 3b*) rather than by some other mechanism (i.e., a series of straps). Also, the exercise benches were located approximately 1.5 m from the sudden loading apparatus. Therefore, the time between the end of the fatiguing intervals and the beginning of the loading trials was minimal (i.e., approximately 5 s).

Test Trials

Prior to performing the MVCs, the experimental protocol was explained to the subject, and then the subject was allowed three practice trials of each of the load timing conditions (T_K and T_R). After the MVCs were performed, the test trials began. The trials were performed in blocks of 10, with participants performing 10 consecutive trials of each of the T_K and T_R conditions for the F_0 , F_E and F_{EF} conditions. Subjects performed 10 T_K trials and 10 T_R trials in the rested state. The same was repeated for the F_E and then for the F_{EF} conditions. Following each block of trials, a break or fatiguing interval was performed, as outlined below in *Figure 4 (p. 47)*. The order of T_K and T_R was randomized within each fatigue condition. However, due to the fatiguing protocol, the order of rest and fatigue could not be randomized. All randomizations were determined prior to testing.

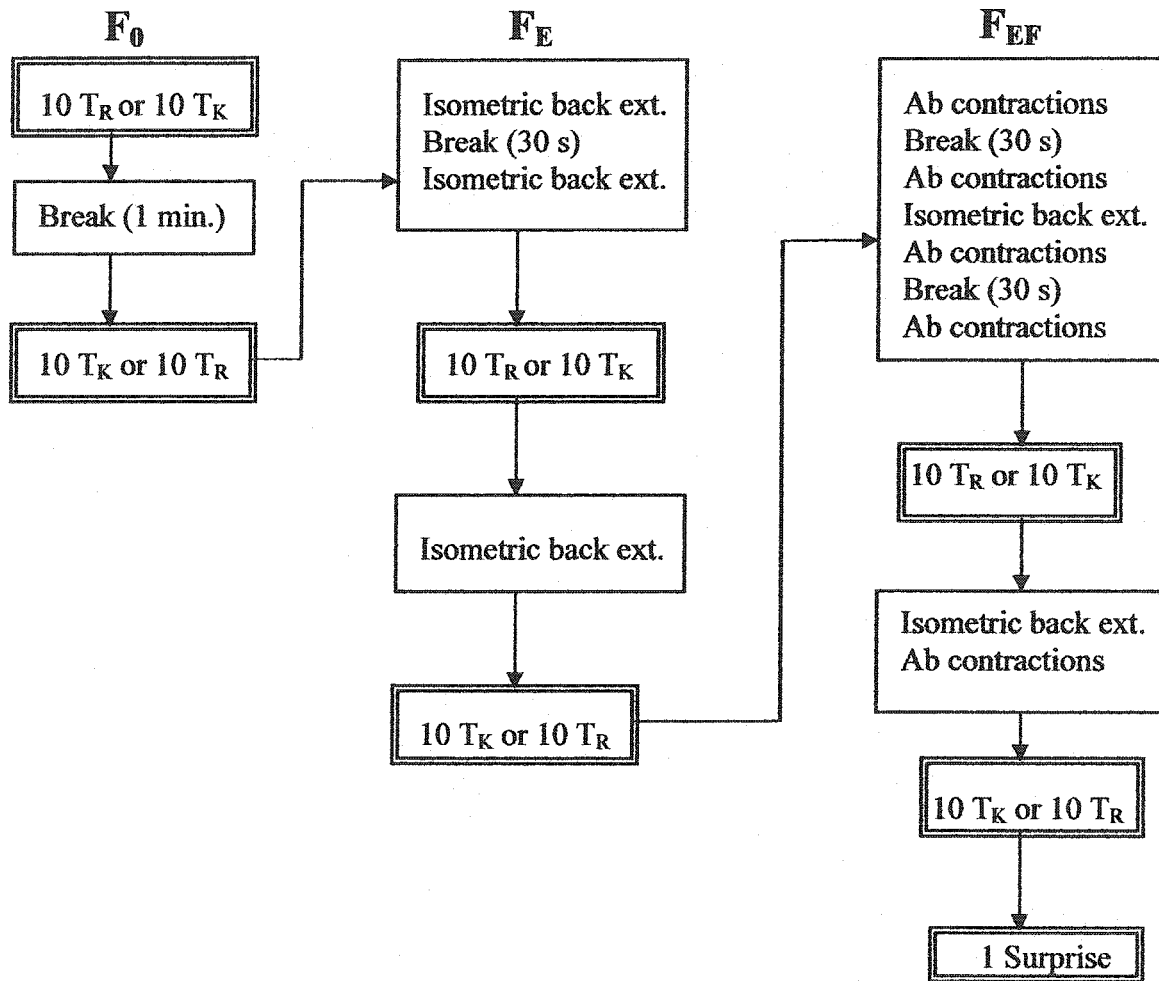


Figure 4. A flow chart depicting the order of the test trials and the fatiguing protocol. Only the order of the T_K and T_R conditions within each fatigue condition could be randomized. Each interval of abdominal contractions involved the two 3-s isometric contractions and the crunches (toward the centre and toward each side).

For the T_K condition, the experimenter would count down from five and release the load on the count of one. This countdown remained unchanged for this condition. For the T_R condition, however, the participants were told that the sudden loading would occur at random times within a 10-second window. A new 10-second window would start immediately after the load hit the bottom of the bin on the previous trial.

Immediately following the last F_{EF} block of trials, a Surprise trial was performed. Contrary to the T_R trials, this single Surprise trial was unexpected for a different reason,

as participants falsely believed that they knew the timing of the perturbation. At the end of the experiment, the participants were told that a couple more T_K trials were needed to make sure that there was enough data. The countdown was identical to that of the T_K trials, except that instead of dropping the load on the count of five, the load was dropped prematurely, unbeknownst to the subject, on the count of three. Because the Surprise trial was deceptive in nature, it could only be performed once and it had to be performed last. Therefore, it could only be performed as an adjunct to the last F_{EF} condition (either $F_{EF}-T_K$ or $F_{EF}-T_R$, depending on the randomization). There was no fatiguing interval performed before this final Surprise trial.

Data Analysis

The current experiment tested the effects of trunk muscle fatigue and expectedness during sudden trunk loading. The independent variable of Fatigue had three levels (F_0 , F_E and F_{EF}), and the independent variable of expectedness or Load Timing had two levels (T_K , T_R), plus the Surprise trial.

Dependent Variables

The dependent variables were divided into Baseline, Pre Response, and Load Response stages. *Figure 5* depicts the time frames of the different stages and the dependent variables. The Pre Response values were calculated by subtracting the average Baseline value from the average “Pre” value. The baseline value was defined as the average during the -300 to -250 ms prior to the loading. The “Pre” value was defined as the average value in the -15 ms just prior to the loading. The peak responses in the Load Response stage were calculated by finding the difference between the “Pre” value and the

peak value post loading. The Peak was defined as the highest filtered value in the 350 ms following the loading for the EMG, or in the 700 ms following the loading for the Trunk Angle and CoP.

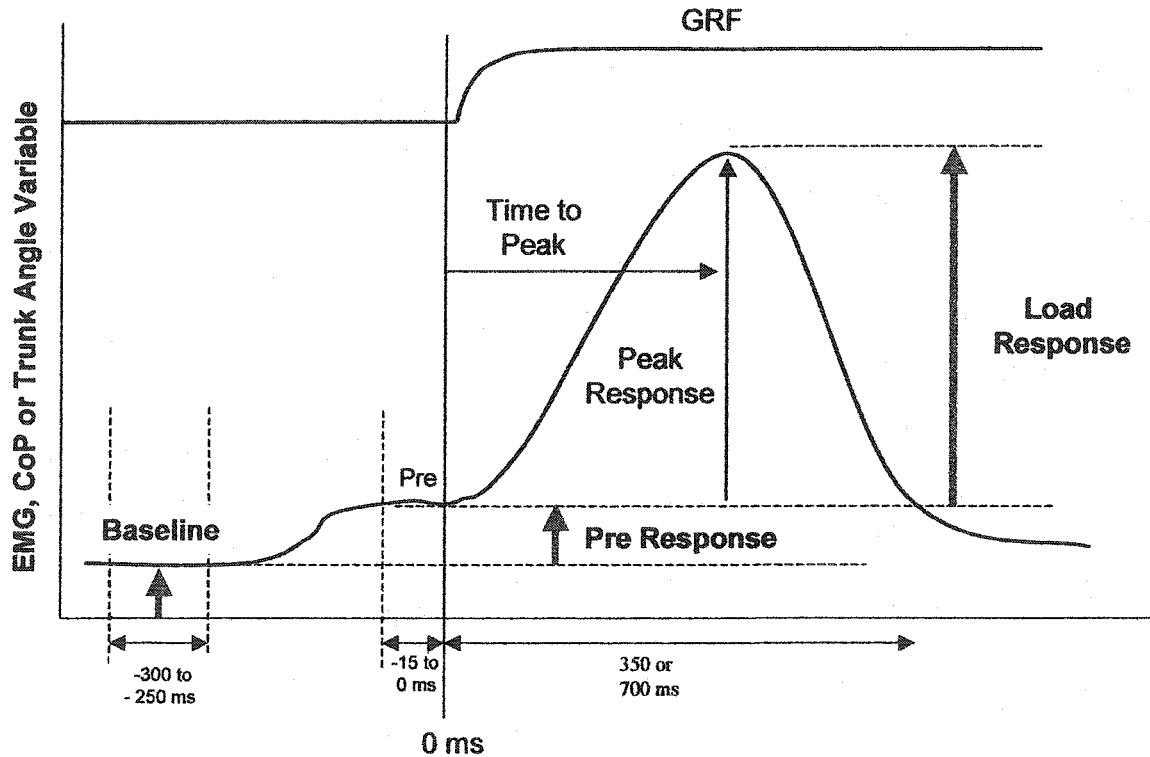


Figure 5. Sample graph depicting the different stages of the loading trials and the dependent variables. The change in the vertical GRF denoted when the loading occurred (0 ms). The duration of the Load Response phase was 350 ms for the EMG, and 700 ms for the CoP and Trunk Angle data.

The duration of the Load Response phase was determined by visually inspecting the data. Enough time was allowed so that the entire response was captured without “cutting off” the peaks. However, an excessively long Load Response phase would have incorporated the voluntary responses in addition to the reflexive responses, which was not desired in this experiment.

Moreover, the vertical GRF was used to determine when the sudden load occurred, as there was a sudden increase in the GRF as the weight landed in the bin. However, although the trigger was determined by using the sudden increase in the GRF, the load was felt at the trunk earlier than it was recorded on the force plate. This is due to the fact that the load was applied to the hands, and that the impact had to travel through several segments of the body before reaching the force plate. Prior to the data analysis, the extensor EMG activity and the Trunk Angle graphs during the T_R and Surprise trials were visually inspected. It had to be assumed that the participants had no way of knowing when the loading would occur during these conditions and that, as such, they would not begin to ramp up their back muscle activity prior to the perturbations. The sudden increases in the EMG and in the Trunk Angle were quite obvious.

Upon visually inspecting the data, it was found that, on average, the delay between the activation of the back muscle EMG or the trunk displacement and the GRF trigger was approximately 50 ms. Thus, during the data analysis, 50 ms was subtracted from the GRF trigger time to more accurately represent the *true* loading time of the trunk. The dependent variables mentioned above were all computed according to this time, which was defined as time 0. During the data analysis, the GRF curves were displayed with high resolution, and the trigger (the sudden increase in the GRF) was visually determined with a cursor. Trials with a gradual increase in the GRF, or with an increase that was difficult to distinguish, were discarded.

For each dependent variable, an average of the 10 trials was calculated for each subject per condition, and then an average for each condition was calculated across subjects. APAs were quantified by computing the Pre Response CoP and Trunk Angle data. Specifically, in the Baseline stage, the Mean CoP Location and the Mean Trunk

Angle were computed. In the “Pre” stage, the Mean CoP Displacement and the Mean Angular Trunk Displacement were calculated. The Baseline values were then subtracted from the “Pre” values to get Pre Response values. This Pre Response would measure the degree to which participants adjusted their posture just before the sudden loading. Similarly, cocontraction in anticipation of the loading was quantified by subtracting the Baseline Mean Normalized EMG (NEMG) from the “Pre” Mean NEMG to get a final Pre Response Mean NEMG value.

Moreover, to compare the effects of the perturbation in the Load Response stage, Peak CoP Displacement, Peak Angular Trunk Displacement, and Peak NEMG were calculated. Also in the Load Response stage, the Time-to-Peak (TtPk) NEMG, TtPk CoP Displacement, and TtPk Angular Trunk Displacement were calculated. These were calculated by subtracting the average “Pre” values from the Peak values. Also, the TtPk values were recorded by measuring the duration from time 0 to the time at which the peak value occurred. The results from the Load Response stage reflected the ability of the sudden load to perturb the system. Whereas *Figure 5* graphically depicted how the dependent variables were calculated, *Table 1* provides a list of the various measures.

Table 1. Table presenting the three loading stages (Baseline, Pre Response and Load Response), and the dependent variables within each stage. The TtPk values were calculated from time 0 ms.

BASELINE (-300 to -250 ms)	Mean CoP
	Mean Trunk Angle
	Mean NEMG
PRE RESPONSE (Pre 15 ms - Baseline)	Mean Change in CoP
	Mean Change in Trunk Angle
	Mean Change in NEMG
LOAD RESPONSE (Peak - Pre 15 ms)	Peak CoP & TtPk CoP
	Peak Trunk Angle & TtPk Trunk Angle
	Peak NEMG & TtPk NEMG

Quantification of Fatigue

Fatigue was defined as having been reached when the subject could no longer perform the fatiguing contractions. However, MPF and EMG amplitudes were also collected as a way to quantitatively ascertain that a high level of fatigue had been attained. In terms of the EMG amplitude, the percent difference in the initial average amplitude and the final average amplitude was calculated. The initial value was taken within the first 3 s of the fatiguing contraction, and the final value was taken during the last 3 s of the fatiguing contraction. A mean difference was then calculated for each set of muscle contractions for each muscle. Similarly, for the MPF, an average MPF was calculated for the first and last 3 s of each set of muscle contractions. From these values, a percent decline in the MPF could be obtained. For the both EMG amplitude and the MPF data, mean changes and standard deviations were then calculated across all subjects for each set of muscle contractions for each muscle separately.

Statistics

To test for main and interaction effects between conditions, a 3x2 ANOVA (3 fatigue levels x 2 load timing levels) with repeated measures was performed. The Surprise condition was not analyzed in the ANOVA, but, instead, means and standard deviations were computed and trends in the data were extracted. The 3x2 design is illustrated in *Figure 6*. Significance was set at $p < 0.05$. When a significant interaction effect was found, a series of *t*-tests was performed post-hoc with the Bonferroni Correction.

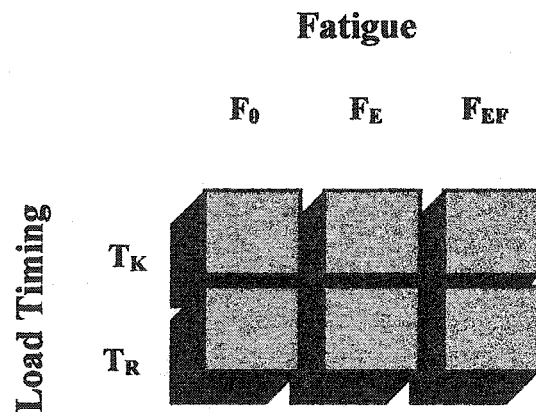


Figure 6. A diagram of the 3x2 statistical design. There were three levels of Fatigue (F_0 , F_E and F_{EF}) and two levels of Load Timing (T_K , T_R) in the ANOVA.

Chapter 4

RESULTS

Measurement of Fatigue

Prior to reviewing the results of the current study, it is important to describe the level of fatigue that was reached by the participants. In the current experiment, not only did participants perform the exercises until the point of exhaustion, but the exercises were repeated throughout the testing session, as previously described.

Mean Power Frequency

Fatigue, in the current experiment, was defined as being attained when participants reached volitional fatigue. Nonetheless, MPFs were recorded to provide quantitative evidence that muscle fatigue was present. Percent declines in the MPFs are presented for the back muscles (LES and TES) during the back fatiguing intervals, and for the abdominal muscles (EO and IO) during the abdominal fatiguing intervals. The means and standard deviations were computed and can be viewed in *Appendix B*. The mean percent decline in the MPF for the TES muscle across all subjects was 17% during the first extensor fatiguing interval. Similarly, the first fatiguing interval yielded a mean decrease of 25% for the LES. Note that the subsequent fatiguing intervals also maintained a notable decrease in the MPF for both the TES and LES muscles, ranging between 17-25% for the TES, and between 21-25% for the LES.

Furthermore, the mean percent decline in the MPF across all subjects was 17% for the EO and -3% for the IO during the first flexor fatiguing interval. The EO also maintained a notable decrease in MPF during the second abdominal fatiguing interval

(15%). However, according to the MPF measure for the IO, this muscle did not seem to fatigue during the abdominal exercises. Additionally, it can be assumed that the EO and IO muscles were not markedly fatigued during the F_E fatiguing intervals, as they were only slightly active. Activation levels could be retrieved for nine of the fifteen subjects, and the mean EMG values were 9% of MVC for both the EO and IO muscles.

Experimental Results

For clarity and ease of interpretation, the results will be presented according to the three main loading phases: Baseline, Pre Response and Load Response. The Pre Response phase was calculated with the 15 ms just prior to the sudden trunk loading. The Load Response phase will be further subdivided into the Peak Response and the TtPk Response. Within each of these categories, the EMG, Trunk Angle, and CoP data will be presented. The significant effects ($p < 0.05$) can be viewed in a table at the end of each section. The means and standard error values for all the main effects can be found in *Appendix C*. In addition, the means and standard deviations for the Surprise data, and also a comparison of the Surprise means with the T_K and T_R means can be viewed in *Appendix D*. Standard errors were computed for the Repeated Measures variables, whereas standard deviations were computed for those variables that were not Repeated Measures. The Surprise means are compared to the T_K and T_R means for the F_{EF} condition only, as the Surprise trial was always performed as an adjunct to the last F_{EF} loading trial. Only descriptive (and not statistical) data are presented for the Surprise condition, and only when a significant effect of *Load Timing* was found. In other words,

if there was no difference between the T_K and T_R conditions, then there was no reason to compare the Surprise mean to the T_K and T_R means.

Baseline

There were no interactions between *Fatigue* and *Load Timing* for any of the Baseline variables tested. Also, there were no significant main effects for *Load Timing*, and no main effects for the Trunk Angle variable, specifically.

EMG

As presented in *Table 2 (p. 59)*, there was a main effect of *Fatigue* in the Baseline Mean NEMG activity of the TES, $F(2, 14) = 15.057$, $p < 0.0001$ (*Figure 7*). The post-hoc tests revealed that significant differences existed between each of the fatigue conditions, such that the Baseline Mean NEMG was lowest in the F_0 condition, and then increased by 17% in the F_E condition, and again by 16% in the F_{EF} condition. Therefore, the F_{EF} condition was 36% higher than the F_0 condition. The results of the post-hoc tests can be viewed in *Table 2 (p. 59)*.

Moreover, there was a significant main effect of *Fatigue* for the LES muscle, $F(2, 14) = 5.729$, $p = 0.0087$ (*Figure 7*). Specifically, the activity was lowest in the F_0 condition and then increased by 20% in the F_E condition, and by 23% in the F_{EF} condition. The F_E and F_{EF} conditions, however, were not significantly different from each other.

In addition, there was a main effect of *Fatigue* for the EO muscle, $F(2, 14) = 6.362$, $p = 0.0053$, whereby the Baseline Mean NEMG value was significantly higher in the F_E and F_{EF} conditions as compared to the F_0 condition, by 16% and 18%, respectively

(Figure 7). Again, however, the F_E and F_{EF} conditions were not significantly different from each other.

Finally, there was also a main effect of *Fatigue* for the IO muscle, $F(2, 14) = 3.675$, $p = 0.0383$ (Figure 7). The Baseline Mean NEMG was significantly higher by 20% in the F_{EF} condition versus the F_0 condition. Although the difference between the F_0 and the F_E conditions was not significant, there was a strong trend showing higher EMG activity in the F_E condition. Also, the F_E and F_{EF} conditions were not significantly different from each other.

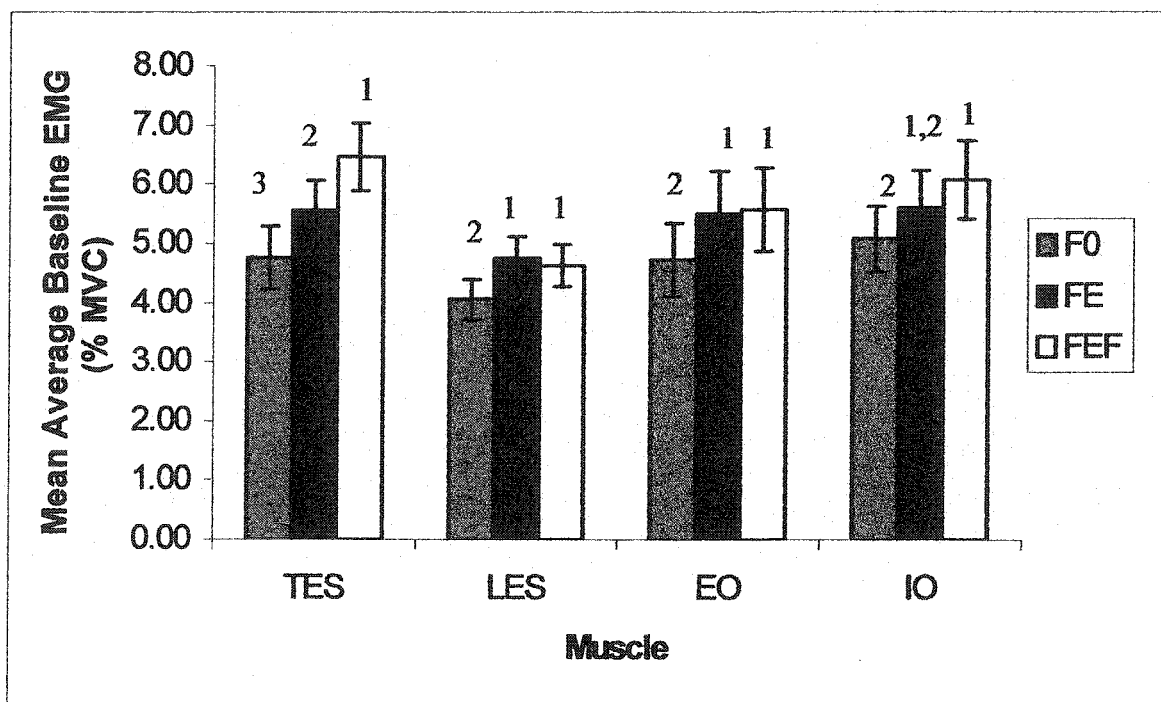


Figure 7. Main effect of *Fatigue* across muscles for the Mean NEMG during the Baseline phase ($n = 15$). Standard error bars are also presented. Significant differences are indicated by different numbers above the bars ($p < 0.05$).

CoP

For the Baseline Mean CoP, there was a main effect of *Fatigue*, $F(2, 14) = 4.784$, $p = 0.0163$ (*Figure 8*). Specifically, the Mean CoP was significantly lower in the F_E condition than in the F_0 condition by 35%, and also higher in the F_{EF} condition than in the F_E condition by 57%. This means that subjects tended to shift their CoP more forward in the F_0 and F_{EF} conditions prior to the loading. Note, however, that the F_0 and F_{EF} conditions were not significantly different from each other. Also, all the mean values were in the positive (anterior) direction. *Table 2* summarizes the significant main effects and the post-hoc analyses for the Baseline data.

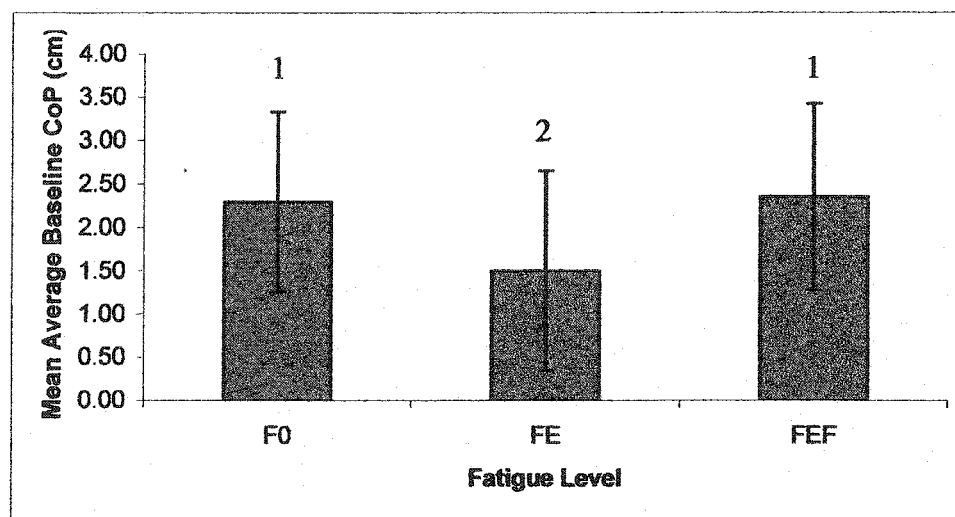


Figure 8. Main effect of *Fatigue* for the Baseline Mean CoP ($n = 15$). Standard error bars are also presented. Significant differences are indicated by different numbers above the bars ($p < 0.05$).

Table 2. Summary of the significant main effects of *Fatigue* ($p < 0.05$) and the significant post-hoc analyses (Bonferonni adjusted p -value = .017) for the Baseline data. p -values are presented only when significant effects were found ($n = 15$). An asterisk (*) signifies that there was a strong trend in the data that failed to reach significance.

	Main Effect <i>Fatigue</i>	Post-hoc Comparisons
TES	$p < 0.0001$	$F_0 < F_E$ ($p < 0.01$), $F_0 < F_{EF}$ ($p < 0.0001$), $F_E < F_{EF}$ ($p < 0.01$)
LES	$p < 0.01$	$F_0 < F_E$ ($p < 0.01$), $F_0 < F_{EF}$ ($p < 0.01$)
EO	$p < 0.01$	$F_0 < F_E$ ($p < 0.01$), $F_0 < F_{EF}$ ($p < 0.01$)
IO	$p < 0.05$	$F_0 < F_{EF}$ ($p < 0.01$), $F_0 < F_E$ ($p = 0.0454$)*
Trunk Angle	ns	—
CoP	$p < 0.05$	$F_0 > F_E$ ($p < 0.01$), $F_E < F_{EF}$ ($p < 0.001$)

Pre Response

There were no significant main effects of *Fatigue* for the Pre Response data. Also, there were no main effects for any of the EMG variables studied.

Trunk Angle

There was a main effect of *Load Timing* for the Pre Response Mean Change in Trunk Angle, $F(1, 14) = 5.425$, $p = 0.0421$ (*Figure 9*). Although the Mean Change in Trunk Angle was 98% lower in the T_R condition compared to the T_K condition, the actual magnitude of this difference was quite small (approximately 0.1°). The mean Pre Response in the Surprise condition (mean = -0.003°) was similar to the mean Pre Response in the T_R - F_{EF} condition (mean = -0.045°), and was also slightly negative in direction. However, the Surprise mean was lower than the T_K - F_{EF} mean (mean = 0.173). Furthermore, there was a significant interaction effect for the Pre Response Mean Change in Trunk Angle, $F(2, 14) = 7.427$, $p = 0.0039$ (*Figure 9*). However, none of the post-hoc

comparisons of interest here (regarding the effect of fatigue on each load timing condition) reached significance..

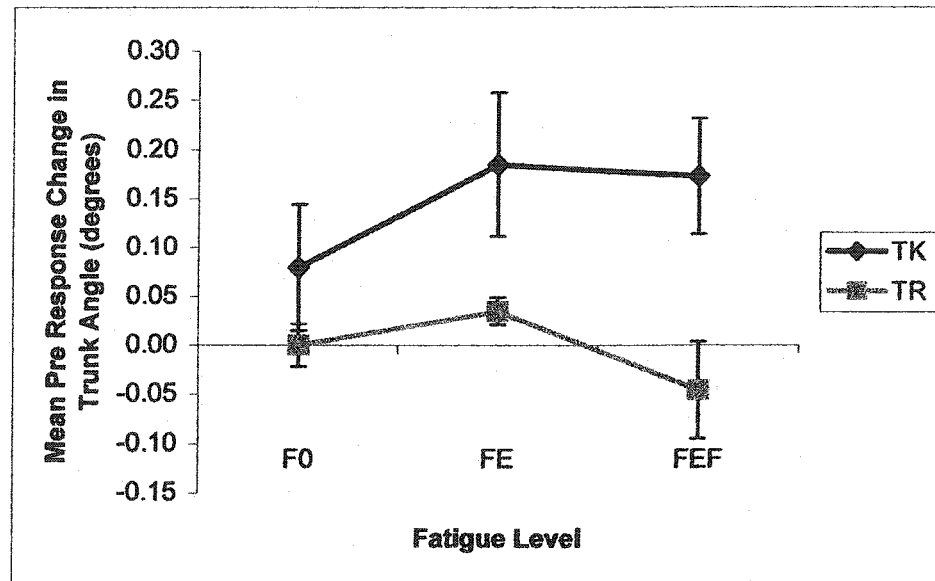


Figure 9. Significant interaction effect ($p < 0.05$) of *Load Timing* x *Fatigue* for the Pre Response Trunk Angle data ($n = 15$). Standard error bars are also presented.

CoP

There was a main effect of *Load Timing* for the Pre Response Mean Change in CoP, $F(1, 14) = 18.287$, $p = 0.0008$ (*Figure 10*). Again, although the Mean Change in CoP was 93% less in the T_R condition versus the T_K condition, the actual magnitude of this difference was quite small (approximately 0.1 cm). Although the T_R condition displayed values that were less negative, both averages were negative, signifying an overall shift in the posterior direction. Moreover, the Mean Change in CoP in the Surprise condition (mean = -0.049 cm) was similar to the Mean Change in the T_R -FEF condition (mean = -0.030 cm), but lower than the Mean Change in the T_K -FEF condition (mean = -0.161 cm). *Table 3* summarizes the significant main effects and the means comparisons for the Pre Response data.

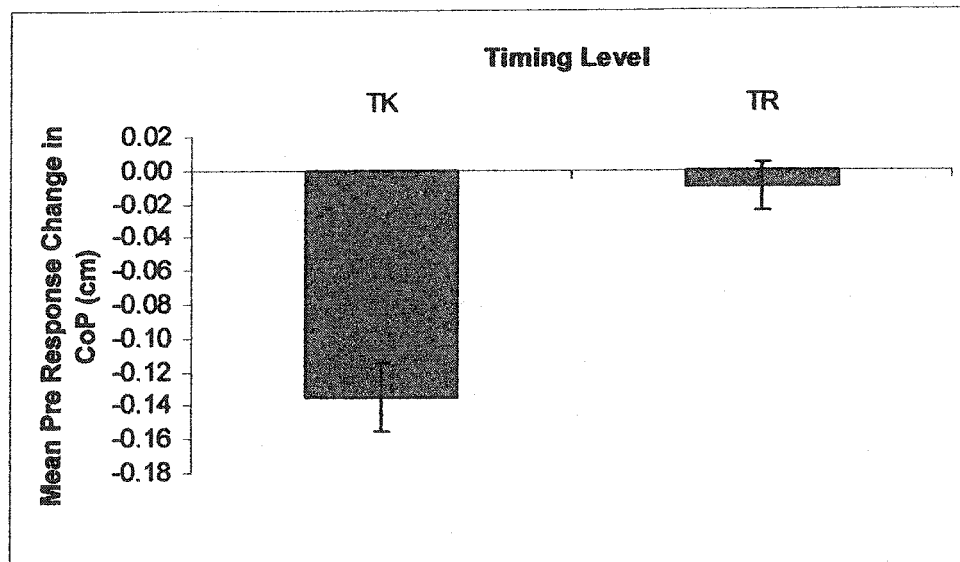


Figure 10. Significant main effect ($p < 0.05$) of *Load Timing* for the Pre Response CoP data ($n = 15$). Standard error bars are also presented.

Table 3. Summary of the significant main effects of *Load Timing* ($p < 0.05$) and the means comparisons for the Pre Response data ($n = 15$). p -values are presented only when significant effects were found. Note that there were no significant effects for the EMG data.

	Main Effect Load Timing	Means Comparisons
TES	ns	—
LES	ns	—
EO	ns	—
IO	ns	—
Trunk Angle	0.0421	$T_K > T_R$
CoP	0.0008	$T_K > T_R$

Peak Response

There were no significant interaction effects for any of the Peak Response variables.

EMG

There was a main effect of *Load Timing*, $F(1, 14) = 4.98$, $p = 0.0425$ for the Peak NEMG of the TES muscle (*Figure 11*). Specifically, the activity of the TES was 10% higher in the T_R condition than in the T_K condition. Also, the mean Peak activity of the TES was lowest in the Surprise condition (Surprise mean = 14.011, T_K - F_{EF} mean = 15.000, T_R - F_{EF} mean = 16.638).

Furthermore, there was a main effect of *Load Timing* for the Peak NEMG of the LES muscle, $F(1, 14) = 10.3$, $p = 0.0068$ (*Figure 11*). The muscle activity in the T_R condition was higher than in the T_K condition by 9%. The mean Peak activity of the LES in the Surprise condition (mean = 11.047) was lower than in the T_R - F_{EF} condition (mean = 12.570), but similar to that in the T_K - F_{EF} condition (mean = 10.803).

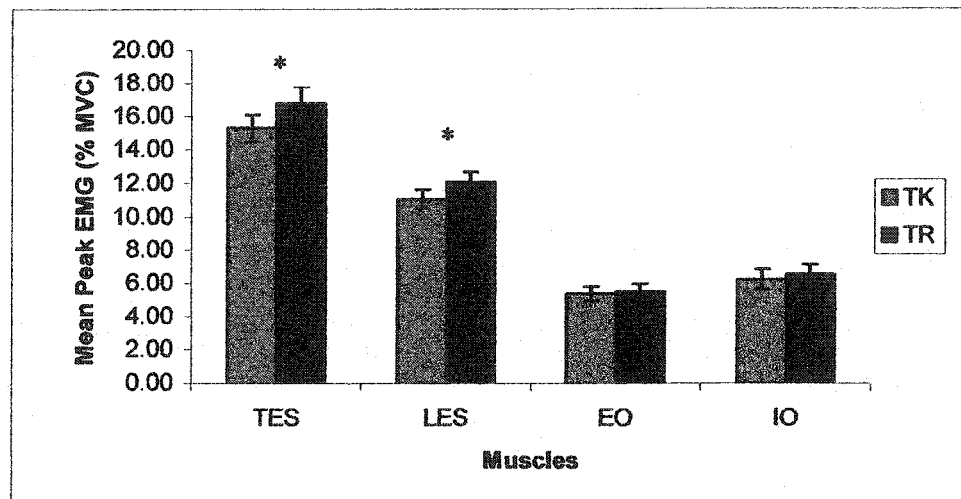


Figure 11. Main effect of *Load Timing* for the Peak Response NEMG data ($n = 15$). An asterisk (*) denotes significance ($p < 0.05$). Standard error bars are also presented.

Trunk Angle

There was also a significant main effect of *Load Timing* for the Peak Trunk Angle, $F(1, 14) = 22.029$, $p = 0.0008$ (*Figure 12*). The Peak Trunk Angle was 27% higher in the T_R condition than in the T_K condition, and both averages were positive (anterior) in direction. However the magnitude of this change was small, given that the inherent error in the goniometer is $\pm 2^\circ$. Also, note that the mean Peak Trunk Angle was higher in the Surprise condition (mean = 5.701°) than in the T_K - F_{EF} condition (mean = 5.193°), but lower than in the T_R - F_{EF} condition (mean = 6.046°).

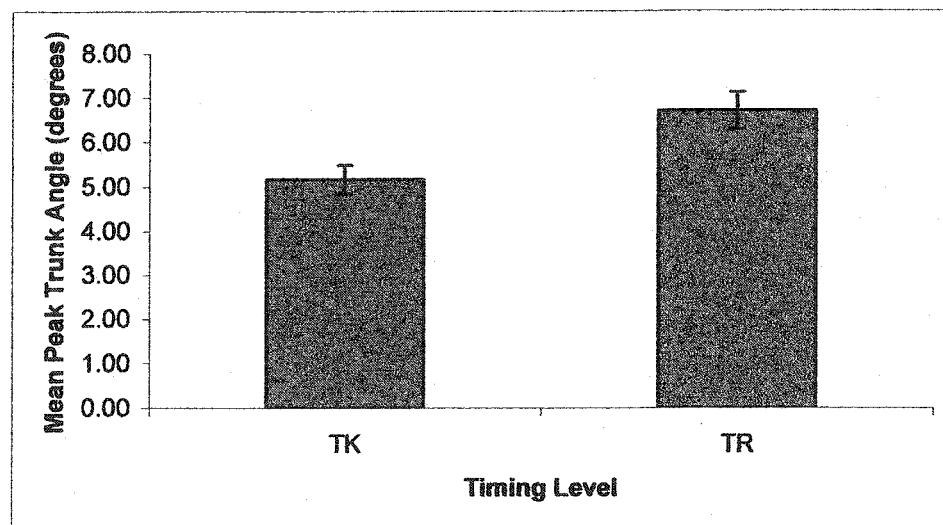


Figure 12. Significant main effect ($p < 0.05$) of *Load Timing* for the Peak Response Trunk Angle data ($n = 15$). Standard error bars are also presented.

CoP

In terms of the Peak CoP, the two main effects were significant, $F(1, 14) = 27.597$, $p = 0.0001$, and $F(2, 14) = 5.437$, $p = 0.0101$ for the effect of *Load Timing* (*Figure 13*) and *Fatigue* (*Figure 14*), respectively. Also, all the mean Peak CoP measures were in the negative (posterior) direction. The Peak CoP was 13% higher in the T_R condition than in the T_K condition. The mean Peak CoP in the Surprise condition

(mean = -8.702 cm) was higher than in the other two conditions (T_K-F_{EF} mean = -4.517 cm, T_R-F_{EF} mean = -5.127 cm). Furthermore, the Peak CoP was 5% lower in the F_{EF} condition than in the F_0 condition, and so the values in the F_{EF} condition were less negative (less posterior) in direction. *Tables 4a* and *4b* summarize the significant main effects and the post-hoc analyses for the Peak Response data.

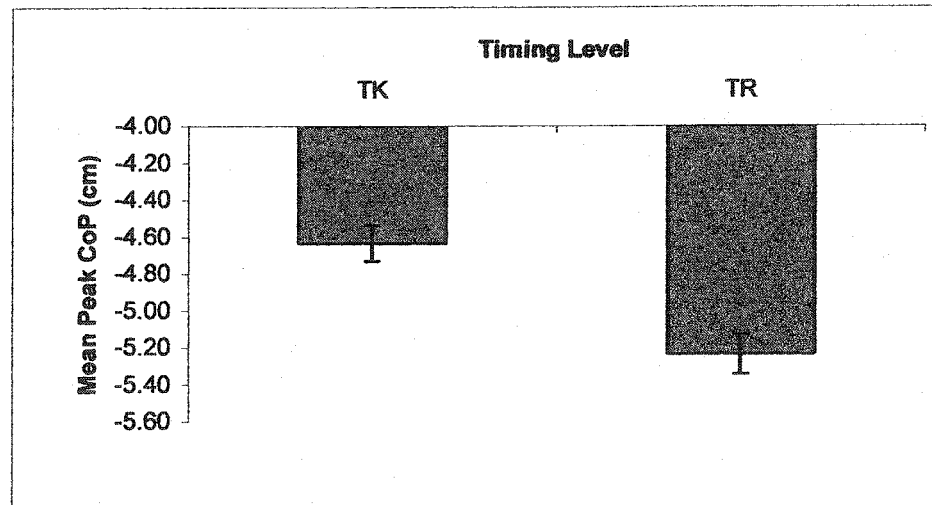


Figure 13. Significant main effect ($p < 0.05$) of *Load Timing* for the Peak Response CoP data ($n = 15$). Standard error bars are also presented.

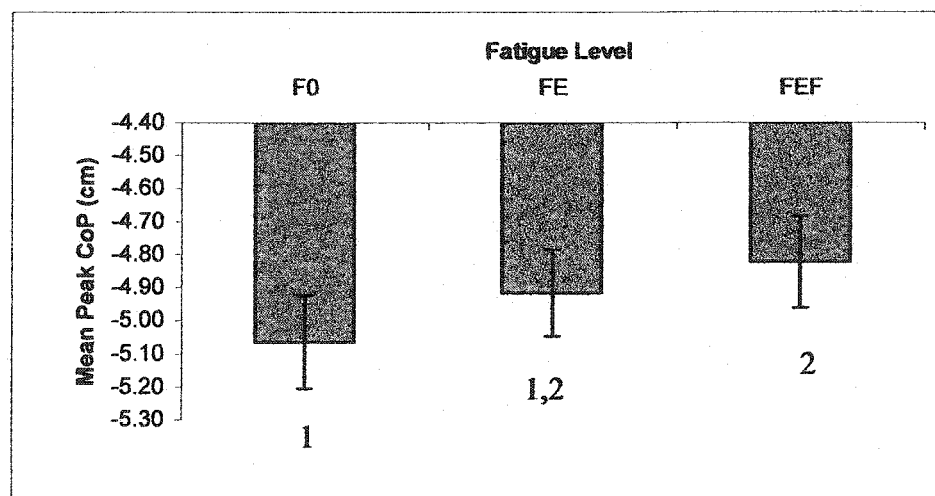


Figure 14. Main effect of *Fatigue* for the Peak Response CoP data ($n = 15$). Standard error bars are also presented. Significant differences are indicated by different numbers below the bars ($p < 0.05$).

Table 4a. Summary of the significant main effects of *Load Timing* ($p < 0.05$) and means comparisons for the Peak Response data. p -values are presented only when significant effects were found ($n = 15$).

	Main Effect <i>Load Timing</i>	Post-hoc Comparisons
TES	0.0425	$T_K < T_R$
LES	0.0068	$T_K < T_R$
EO	ns	—
IO	ns	—
Trunk Angle	0.0008	$T_K < T_R$
CoP	0.0001	$T_K < T_R$

Table 4b. Summary of the significant main effects of *Fatigue* ($p < 0.05$) and the post-hoc comparisons (Bonferonni adjusted p -value = .017) for the Peak Response data. p -values are presented only when significant effects were found ($n = 15$).

	Main Effect <i>Fatigue</i>	Post-hoc Comparisons
TES	ns	—
LES	ns	—
EO	ns	—
IO	ns	—
Trunk Angle	ns	—
CoP	0.0101	$F_0 > F_{EF}$ ($p < 0.01$)

Time-to-Peak Response

Note that there were no significant interaction effects or main effects of *Fatigue* for all the TtPk measures.

EMG

Similar to the peak amplitude EMG data, there was a main effect of *Load Timing* in the TtPk measure of the NEMG of the LES, $F(1, 14) = 7.117$, $p = 0.0193$. The T_R condition was 11% slower than the T_K condition (*Figure 15*). Moreover, the mean TtPk in the Surprise condition (mean = 208 ms) was longer than in the other two conditions ($T_K - F_{EF}$ mean = 172 ms, $T_R - F_{EF}$ mean = 195 ms).

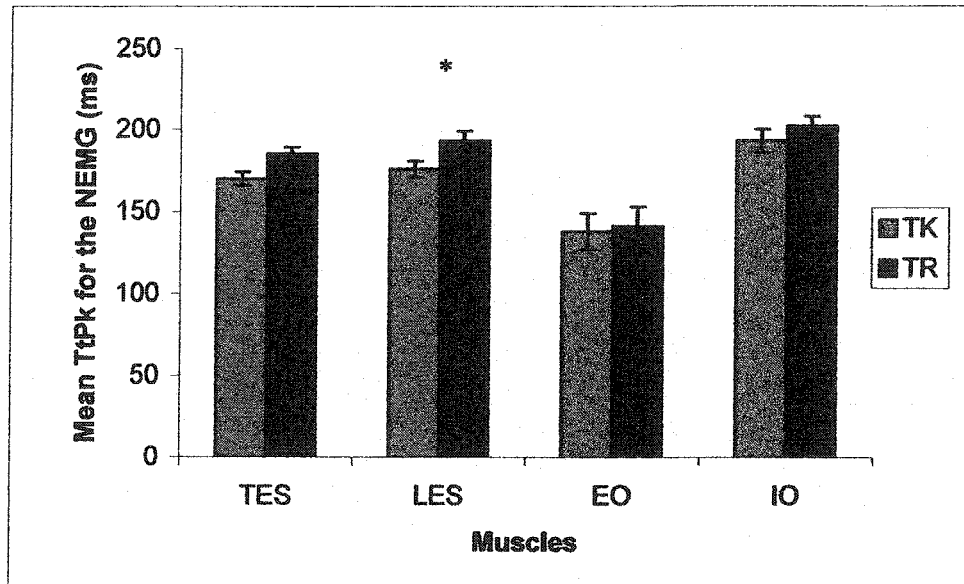


Figure 15. Main effect ($p < 0.05$) of *Load Timing* for the TtPk Response NEMG data ($n = 15$). An asterisk (*) denotes significance ($p < 0.05$). Standard error bars are also presented.

CoP

Moreover, there was a main effect of *Load Timing* for the CoP measure, $F(1, 14) = 10.043$, $p = 0.0068$, which showed that the TtPk was 8% quicker in the T_R condition than in the T_K condition (*Figure 16*). The mean TtPk for the CoP measure in the Surprise condition (mean = 492 ms) was shorter than in the T_K - F_{EF} condition (mean = 506 ms), but longer than in the T_R - F_{EF} condition (mean = 479 ms). *Table 5* summarizes the significant main effects and the means comparisons for the TtPk Response.

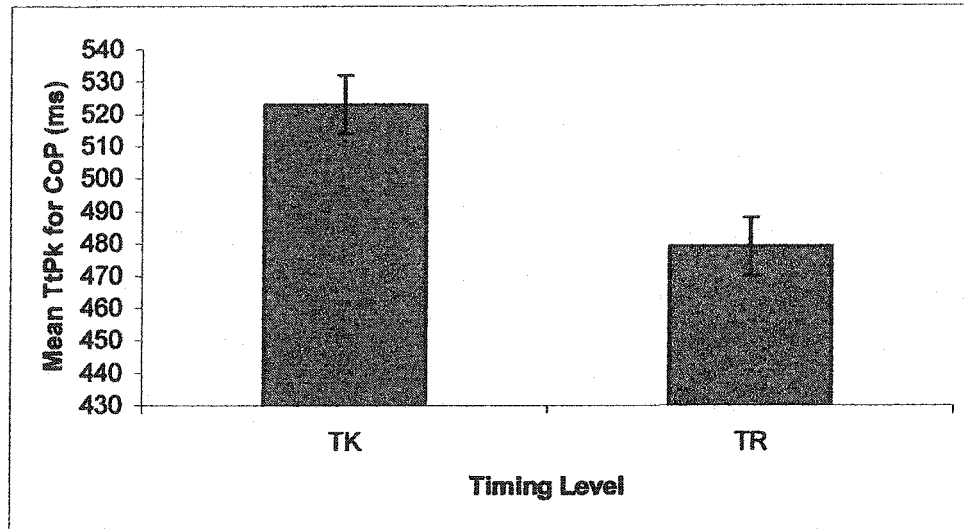


Figure 16. Significant main effect ($p < 0.05$) of *Load Timing* for the TtPk Response for the CoP data ($n = 15$). Standard error bars are also presented.

Table 5. Summary of the significant main effects of *Load Timing* ($p < 0.05$) and the means comparisons for the TtPk data. p -values are presented only when significant effects were found ($n = 15$).

	Main Effect <i>Load Timing</i>	Means Comparisons
TES	ns	—
LES	0.0193	$T_K < T_R$
EO	ns	—
IO	ns	—
Trunk Angle	ns	—
CoP	0.0068	$T_K > T_R$

Chapter 5

DISCUSSION

The current experiment had some significant findings, but it also raised a number of questions. Generally speaking, although statistically significant, the presence of Trunk Angle and CoP APAs were minimal. Also, there was no significant increase in muscle cocontraction just prior to anticipated loading. These findings suggest that the impact of the sudden load was too small to elicit APAs in the trunk and whole-body. Or, perhaps other segments of the body (namely the lower limbs) may have been involved in preparing for the perturbation, as indicated previously (Haumann, 2002; Brown et al., in press). The presence of APAs in other segments of the body is supported by the fact that the Peak Responses following the perturbation were higher in the T_R condition than in the T_K condition. This means that participants must have been able to prepare for the T_K condition in some way.

Furthermore, trunk muscle fatigue led to an increase in the Baseline activity of the trunk muscles, but not in additional muscle activity just prior to the sudden loading. This suggests that there may have been increased spinal stiffness from the beginning of the loading trial (whenever the subjects were fatigued), and not just immediately prior to the perturbation. Moreover, fatigue had no effect on the Peak Responses of the trunk muscles, implying that the body successfully adapted to the fatigue prior to the perturbation. The $TtPk$ variable was also not altered with fatigue, although there may have been changes in the muscle onset latencies that were not captured in the current experiment. These findings will be discussed in greater detail in the sections that follow.

Hypotheses Revisited

In this section, each of the hypotheses will be addressed with regard to the current results. Also, as warranted, previous literature will be compared to the findings of the current experiment.

1. *APAs will be significantly greater in the known timing condition (T_K) than in the random timing condition (T_R).*

The current study rejected the first hypothesis for both the trunk and whole-body (CoP). Recall that APAs are defined as adjustments in posture prior to a perturbation, represented here by the Pre Response data. APAs serve to minimize the effects of a perturbation and to optimize coordination. The effect of *Load Timing* on the Pre Response was the same for both the Trunk Angle (*Figure 9*) and for the CoP (*Figure 10*). Although, statistically, there was less of a Pre Response when the load timing was random versus when the timing of the perturbation was known by the participant, the magnitude of this difference was quite small and, therefore, functionally insignificant. Statistically speaking, there was a greater Trunk Angle change in the T_K condition than in the T_R condition. However, given the inherent error in the goniometer used to measure the Trunk Angle ($\pm 2^\circ$), even a change of 0.1° in the T_K condition is very small. Furthermore, in both conditions the CoP was posterior in direction, as it was in the study by Lavender and Marras (1995). Although the difference between the T_K and T_R conditions was statistically significant for the Pre Response CoP, the magnitude of this difference was minor (-0.1 cm) and, therefore, functionally insignificant.

Thus, it is the opinion of this author that there were no APAs in the Trunk Angle and in the CoP in the current experiment, as the differences found in these variables were not functionally relevant. In a similar loading study by Haumann (2002), the effect of *Load Timing* was statistically significant on the Pre Response CoP. Again, however, this effect was not functionally significant, as the shift in the CoP was merely 0.25 cm when the loading was expected. Therefore, in the current experiment, the primary preparatory strategies of the body did not involve the Trunk Angle and CoP. If there were, indeed, preparatory responses associated with the T_K condition, they would have been reflected in other measures, as will be discussed.

2. *The degree of cocontraction prior to the loading will be significantly higher in the known versus random timing condition.*

In the current study, the second hypothesis was rejected. The Pre Response muscle activity did not increase for any of the muscles when the load timing was known. This is contradictory to most other findings in the literature, as it has been well documented that cocontraction of the trunk muscles occurs in anticipation of a known perturbation (Marras et al., 1987; Lavender et al., 1989; Cresswell et al., 1994; Thomas et al., 1998; Krajcarski et al., 1999; Stokes et al., 2000; Haumann, 2002).

3. *The peak responses and the response times of the muscles will be greater following the perturbation in the random versus the known timing condition.*

The third hypothesis was accepted in terms of the Peak Responses of both agonist muscles (*Figure 11*), and in terms of the TtPk Response of one of the agonist muscles (*Figure 15*). It does appear that there were more profound responses with random timing.

The Peak Response following the loading was greater in the T_R condition than in the T_K condition for both the TES and the LES muscles. However, the TtPk Response was higher in the T_R condition versus the T_K condition, but only for the LES muscle. Although no significant results were found for any of the antagonist (flexor) muscles, there were increases in the peak flexor activity in the T_R condition that failed to reach significance. These increases may have been functionally important in terms of helping to stabilize the spine due to the increased extensor activity (*Figure 11*).

According to the literature, anticipation of a sudden load has been shown to lead to lower muscle forces, slower rates of muscle activity onset (Marras et al., 1987; Lavender et al., 1989), and shorter durations of exertion (Marras et al., 1987) following the perturbation. These statements are supported by the findings in the current experiment, with the exception of the TtPk Response of the LES muscle, which was longer in the T_R condition than in the T_K condition. In fact, although the differences were not always significant, all the muscles showed similar patterns of activation with a longer TtPk and a higher peak activation in the T_R condition, as compared to the T_K condition.

4. *When the loading is anticipated (T_K condition), APAs will be lowest in the rested (F_0) condition, followed by the extensor fatigue condition (F_E) and then by the flexor-extensor fatigue condition (F_{EF}).*

The fourth hypothesis was rejected. Although there was a significant interaction effect found for the Pre Response Trunk Angle data (*Figure 9*), the comparisons of interest here did not yield significance.

A significant effect of fatigue was not found for either of the APA measures (Trunk Angle or CoP). It was originally speculated that, because of the decreased muscle force

capacity that comes with fatigue, the body would have to find other ways to prepare for the sudden load rather than through trunk muscle cocontraction. However, the results show that neither trunk muscle cocontraction nor APAs were employed to prepare for the perturbation as a result of muscle fatigue. Therefore, either the trunk muscle fatigue did not affect the preparation strategies used for the sudden loading, or these preparations may have taken the form of leg or arm muscle contractions. This is especially likely when the trunk muscles were fatigued and, as such, would be less able to prepare for the perturbation. Another possible explanation is that the anticipatory actions associated with fatigue of the trunk muscles was not reflected in the Pre Response phase, and may have occurred earlier. These notions will be discussed further in a later section.

5. The degree of cocontraction prior to loading will be highest in the F_{EF} condition, followed by the F_E condition and then by the F_0 condition.

The fifth hypothesis was accepted, but only in terms of the Baseline (resting) data (*Figure 7*) and not in terms of the cocontraction that would have been seen just prior to the perturbations. The Baseline muscle activity increased between the F_0 and F_E conditions, and also between the F_E and F_{EF} conditions for all the muscles, with the exception for the LES muscle that did not exhibit an increase between the F_E and F_{EF} conditions. All these increases were statistically significant for the TES muscle, but only the differences between the F_0 and F_E conditions, and between the F_0 and F_{EF} conditions were significant for the LES and the EO muscles. Also, only the increase between the F_0 and F_{EF} conditions was significant for the IO, although the increase between the F_0 and F_E conditions just failed to reach significance (*Table 2*). Nonetheless, generally the trends

show an increase from the F_0 condition to the F_E condition, and again from the F_E condition to the F_{EF} condition.

6. *The peak responses and the response times of the muscles following the loading will increase from the F_0 condition to the F_E condition, and again from the F_E condition to the F_{EF} condition.*

The sixth hypothesis was rejected, both in terms of the Peak Responses and the TtPk Responses of the trunk muscles. Specifically, in terms of the Peak Responses, no significant effects of fatigue were noted for the trunk muscles, but the Peak CoP Response was 5% lower in the F_{EF} condition than in the F_0 condition. However, numerically speaking, this difference was quite small (0.2 cm).

Furthermore, the TtPk measures did not increase as a result of fatigue. Although it has been shown that the latency (reaction time) of muscles increases with fatigue (Wilder et al., 1996), it has also been shown that the muscle latency stays the same (Häkkinen & Komi, 1983) or even decreases (Allison & Henry, 2002). The increase in the reaction time found by Wilder et al. (1996) may have been attributed to their method for inducing fatigue. They used vibration to fatigue the erector spinae muscles. Therefore, it is possible that the vibration induced many other effects aside from the muscle fatigue, and that these other effects affected the muscle latencies. Moreover, although Häkkinen and Komi (1983) found that the latencies did not change with fatigue, they also found that the electromechanical delay increased with fatigue.

7. *Generally, the Surprise trials will show trends similar to the T_R trials, with minimal preparation (APAs and cocontraction) and, thus, greater effects immediately following the perturbation (greater peaks and times to peaks).*

The last hypothesis was rejected in the current experiment. General trends in the means will be discussed, mainly in terms of the Peak Responses, as these are the measures where a significant effect of *Load Timing* was generally found.

The Surprise means were not similar to the T_{R-FEF} means for the Peak Responses of the TES and LES muscles. In fact, the mean of the Surprise condition was lower than the T_{K-FEF} and T_{R-FEF} means for the TES muscle. Also, the mean of the Surprise condition was similar to the mean of the T_{K-FEF} condition for the LES muscle, both means being lower than the T_{R-FEF} mean.

Limitations and Assumptions

Sample Used

The sample used in the current study was limited to females who were of typical university age. Caution should be exercised when generalizing the findings of this study to males or to individuals of a much younger or older age.

Limitations of the Fatiguing Protocol

Level of Fatigue

Although the effects of muscle fatigue are very important to examine regarding the mechanics and motor control of the spine, unfortunately, there are several limitations with studying fatigue. In the current experiment, fatigue was defined as having been reached when the participant declared that she could not longer perform the exercise, or when it

was obvious that the participant could no longer maintain the isometric posture required for the exercise. However, volitional fatigue is dependent on factors such as the participant's motivations, perseverance and tolerance for pain and discomfort. Thus, in an attempt to prolong the fatiguing effort, verbal encouragement was consistently given to participants to "keep going" and to "not give up". Also, as reported by Moreau, Green, Johnson and Moreau (2001), pain in the legs, abdomen and neck, and also breathlessness were complaints of participants performing a similar extensor fatiguing exercise. Therefore, in order to minimize this type of discomfort in the current experiment, extra padding was added to the exercise benches around the pelvis, thighs, legs and ankles.

Moreover, although fatigue was defined as being volitional, MPFs were also collected for all the trunk muscles. This was done so that there would be quantitative data that could be used to support the claim that the participants were fatigued. For instance, the mean percent decline in the MPF for the TES and LES muscles was 17% and 25%, respectively, across all subjects during the first extensor fatiguing interval. This is well above the 10% threshold that has been used in the past (Potvin & Norman, 1993). Note, as well, that all the participants verbally expressed that they felt very fatigued, and that many experienced some muscle soreness throughout the subsequent few days. Fatiguing intervals were also repeated between loading conditions, which helped to ensure that participants remained very fatigued throughout the duration of the testing.

Changes in Muscle Recruitment

Furthermore, the muscles studied in the current experiment are very difficult to isolate with traditional strength training and/or fatiguing exercises. Thus, although the muscles that were targeted during the fatiguing exercises were largely the ones that were being fatigued, it is only natural that other muscles would have become involved. For instance, although the abdominal muscles would have been slightly active during the back extensor exercises, both the EO and the IO were active to only 9% of MVC for an average duration of 62 s, which would not be enough to fatigue these muscles. Also, all the subjects claimed that it was the back muscle fatigue during the extensor fatiguing interval, and that it was the abdominal muscle fatigue during the flexor fatiguing interval that caused them to stop the exercise.

In addition, it is very difficult to isolate muscles during a fatiguing exercise because, as muscles fatigue, different (less fatigued) muscles are recruited to perform the same action (Duchêne & Goubel, 1990). Different people may also recruit different muscles to perform the same task, depending on each individual's strengths and weaknesses. In order to maximize the isolation of the flexor and extensor muscles, the exercise benches were designed such that the participants' feet would hook under bars. This helped to limit the involvement of the hip extensors during the trunk extensor exercise as well as the hip flexors during the trunk flexor exercise.

IO Muscle

As indicated previously, judging by the MPF of the IO muscle, this muscle did not seem to fatigue during the flexor fatiguing intervals. The percent decrease in the MPF was -3% and 1% for the first and second abdominal fatiguing intervals, respectively (*Appendix B*). Thus, although the participants obviously felt fatigued, this was not reflected in the IO MPF measure. It is possible, therefore, that the IO muscle was not adequately targeted during the flexor fatiguing exercise.

However, the MPF measure was a bit crude for the abdominal muscles in the current experiment. The MPF was calculated during the dynamic portion of the abdominal exercises and MPF is sensitive to changes in muscle length (Mannion & Dolan, 1996). Furthermore, the large variability in the percent decrease of MPF in the IO muscle ($SD = 21-29$, *Appendix B*) indicates that this is probably an invalid measure of fatigue for this muscle.

Nevertheless, it can still be assumed that a considerable degree of fatigue was reached in the flexor muscle group, given that the participants performed several intervals of the exercise until exhaustion. In addition, according to the results of the experiment, the IO muscle did not respond very differently from the EO. For example, the IO followed the same trend as all the other trunk muscles during the Baseline stage, exhibiting an increase in activity between the F_0 and F_E conditions, and again between the F_E and F_{EF} condition. In fact, the Baseline activity of a muscle, in itself, is a measure of muscle fatigue.

Sudden Loading Posture of the Participants

Participants were given instructions to stand comfortably while holding the bin, with their arms slightly outstretched so that their arms were not resting against their body, and with their elbows flexed to approximately 45°. Although these instructions were clearly given to each subject before (and sometimes during) the testing, there was no quantitative measure taken to ensure that the participants remained precisely in this same position between conditions and even compared to other participants. Recall, however, that participants were asked to stand and respond naturally, and so forcing subjects to remain in a very specific position would have meant that they were not responding in a way that was natural for them and for their particular body type. Similarly, there was no apparatus used to fix the pelvis of the participants, and so the responses of the trunk could not be isolated from the responses of the CoP. However, this can also be viewed as a strength of the study, as it is important to study the control of the trunk and lower limbs as connected segments.

Effect of Learning

It is possible that over the 60 loading trials (approximately) participants became habituated and exhibited learned responses, even during the T_R condition. Lavender et al. (1993) stated that participants were able to partly habituate to repeated perturbations, as the trunk flexion and the estimated spinal compression reduced over the course of the perturbations. To account for the effect of learning in the current experiment, the T_K and T_R conditions were randomized. Also, the T_R condition involved a 10-second window during which the load would drop at various times. The Surprise condition was also included to provide a sudden loading that could not be expected for different reasons, as

participants falsely believed that they knew when the loading would occur. Also, because many differences were found between the T_K and T_R conditions, a considerable degree of anticipation must have been lost in the T_R condition.

Limitations of the Data Analysis

The TtPk was measured in the current experiment rather than the onset latency. The TtPk measure is less precise and does not allow one to determine how fatigue and load timing affect reaction time, specifically. When reviewing the data, an attempt was made to determine onset latencies but, in many instances, it was very difficult to manually determine the point of onset, as it was not obvious. It has been shown that manual determination of muscle activity onset is a preferred method of onset determination (Hodges & Bui, 1996).

Furthermore, it would have been beneficial to find a way to measure the exact time that the weight contacted the bin during the loading. In the current experiment, the time of the loading was calculated by determining the point of sudden increase in the GRF measured by the force plate, minus 50 ms. Hodges, Cresswell and Thorstensson (2001) found that there was a difference of 50 ms between the time of a sudden load to the upper limbs and the time that the perturbation reached the trunk (both measured through motion data). However, this value of 50 ms may not have been accurate for the difference in time between when the load hit the bin and when the GRF suddenly increased. When visually inspecting the trials, subtracting 50 ms from the time of the GRF increase coincided with the point of increase in the EMG of the back muscles during the T_R and Surprise conditions (when the time of the loading could not have been known

by the subjects). Furthermore, a few days following the data collection, six participants performed a series of loading trials identical to the ones performed during testing. This time, a force transducer was placed at the bottom of the bin that was held by the participants. This allowed one to measure the time difference between the sudden increase in the force in the bin versus on the ground (GRF). As such, it was found that the 50 ms value was the most appropriate value to subtract from the GRF trigger to account for this delay. However, this way of determining the time of the sudden load was a bit crude and might explain why more differences in the TtPk and in the Pre Response data were not found. In hindsight, a better method of determining load onset would have involved the use of a trigger located in the bin during the testing session itself, which would have determined exactly when the weight contacted the bin.

Other General Findings and Theories

Effect of Load Timing

Anticipatory Changes

Generally speaking, the responses following the random loading were greater than the responses following the expected loading, and heightened responses such as these may lead to tissue injury (Carlson et al., 1981; Mannion et al., 2000). Because differences were seen in the post-perturbation data, there must have been some type of anticipatory response occurring prior to the perturbation in the T_K condition to cause these differences.

Furthermore, when adding the mean Baseline and the mean Pre Response muscle activations for each variable (*Appendix C*), the sums are nearly identical between the T_K

and T_R conditions. (Recall that the Pre Response data provided here is merely a subtraction of the Baseline average from the “Pre” amplitude average (over the 15 ms prior to load impact)). Therefore, the activation of the muscles just prior to loading was very similar between the T_K and T_R conditions.

The chief anticipatory strategies in the T_K condition probably did not involve trunk muscle cocontraction, Trunk Angle or CoP Pre Response changes. More than likely, APAs and cocontractions occurred in other muscles that were not monitored in the current experiment, especially given the fact that the function of the trunk muscles would have been compromised with fatigue. In an experiment by Haumann (2002), a similar sudden loading protocol was used and, as in the current experiment, the pelvis of the participants was not restricted. Haumann (2002) monitored the activity of the leg muscles in addition to the trunk muscles and found a significant anticipatory effect for the biceps femoris when subjects were aware of the timing of the perturbation. This same effect was found for the biceps femoris in Brown et al. (in press). The study by Brown et al. (in press) involved a sudden unloading protocol, whereby the participant himself dropped the weight, with movement of the pelvis unrestricted. Furthermore, although not statistically significant, in both studies, clear increases in the activity of other leg muscles were also seen in anticipation of the perturbation (Brown et al., in press; Haumann, 2002). Because movement of the pelvis was not restricted in the current experiment, as in the two previous studies, similar preparatory strategies of the leg muscles may have been made here.

In addition, the arms may have also been involved in the generation of preparatory strategies, especially given the relatively low impact of the sudden loading. In a previous study by Shiratori and Latash (2001), changes in activation were observed in all the arm

muscles they measured (anterior deltoid, biceps brachii and flexor carpi ulnaris) prior to catching an anticipated load.

Moreover, it is also possible that there were no APAs in the current experiment because they were not needed. The impact of the load in the current experiment consisted of a 5-kg weight dropped from 2.5 cm, which is much lower than the impact used in other experiments. For instance, Lavender & Marras (1995) found APAs when they used a 5.4 kg weight dropped from 1.1 m, and Thomas et al. (1998) found APAs when they directly loaded the torso of participants from 1 m high and with a weight equal to 5% of the subject's maximum isometric trunk extensor strength. In addition, Lavender et al. (1993) dropped a weight equal to 53.4 N through a total distance of 111.1 m into a bucket held by the participants, leading to the emergence of APAs. Conversely, a relatively low impact was used in the current experiment. This was done to minimize the risk of injury, as the participants were at a greater risk of injury due to the extensive trunk muscle fatigue that they had experienced.

Furthermore, although the magnitude of the anticipatory changes in the Trunk Angle and CoP were minor, they were very consistent. Therefore, if a greater load impact had been used, then it is likely that APAs of substantial magnitude would have been observed. In addition, it is also possible that, because of the low impact of the load, APAs of substantial magnitude may not have occurred in other segments of the body, either. In other words, in order to get substantial APAs in the trunk and whole-body, as well as in the legs, a higher weight may have been required.

APAs as Feed-forward Mechanisms

Recall that in situations of sudden perturbations, there is a feed-forward mechanism prepared in advance by the CNS that can be executed prior to the perturbation in the form of APAs, or after the perturbation as a result of a trigger (i.e., the sudden load). During feed-forward voluntary movements, the signal for a movement is supplied “*ahead of time*” and readies the system for either (a) an upcoming motor command or, (b) the receipt of particular feedback information (Schmidt & Lee, 1999). Although the feed-forward mechanism was not reflected in APAs of the trunk and whole-body, a feed-forward mechanism likely still existed. This mechanism may have manifested in APAs of other segments of the body (as previously mentioned), as well as in the responses of the trunk and whole-body that would have been triggered by the load impact and executed immediately after it. In other words, although APAs probably existed in the legs and arms, there was still likely a feed-forward signal that was sent “*ahead of time*” to the trunk and whole-body CoP that was not executed until the trigger occurred. It is not to say that APAs in the trunk and whole-body CoP did not exist, just that they were of small magnitude, probably due to the relatively light impact of the sudden load. Also, the responses immediately following the perturbation were reflexive in nature, and probably involved a combination of the feed-forward effects that were triggered and the reflexive feedback information from the muscle proprioceptors (i.e., muscle spindles).

TtPk

In terms of the TtPk measure, all the muscles tended to have a greater TtPk in the T_R condition than in the T_K condition (although only the difference in the LES muscle reached significance) (*Appendix C*). Previous authors have examined the onset of muscle activation, which is different than the TtPk measure used here. Along with the onset latency, the TtPk measure also includes a component of the duration of activation. Therefore, based on the results of the LES muscle, although the muscle onset latency may have increased with increasing knowledge of load timing, the actual duration of the activation may have decreased. Both these statements are supported by the literature (Marras et al., 1987; Lavender et al., 1989). A slower onset would allow the muscle more time to react appropriately to the perturbation rather than reacting right away and potentially overshooting. Also, the Peak Responses of the muscles were lower in the T_K condition versus the T_R condition, which means that, not only would the muscles be stressed more slowly when the timing is anticipated, but also to a lesser magnitude, both of which would be beneficial in preventing muscle strain injuries.

In addition, the LES muscle had a shorter TtPk in the T_K condition than in the T_R condition, whereas the finding was opposite for the CoP variable. The shorter TtPk of the CoP in the T_R condition suggests that the reaction of the CoP, although rapid, may have been *uncontrolled* when the timing of the perturbation could not be anticipated. This uncontrolled reaction may have led to an overshoot in terms of the change in the CoP amplitude, as indicated by the heightened Peak Response of the CoP.

The TtPk for all the muscles was considerably shorter than the TtPk for the CoP, which means that the peaks reached by the trunk muscles may have affected the Peak CoP Response. The trunk segment occupies approximately 50% of the body's mass, and

so movements of the trunk, especially quick ones, have a large impact on balance (Oddsson & Thorstensson, 1986). The goal during balance control is to maintain one's centre of mass over the base of support. Therefore, the trunk muscles may have been working to help maintain the CoP within the individual's base of support.

It is also of interest to note that, along with the increases in muscle activity, there were also similar increases in the Peak Responses of the Trunk Angle and CoP, although the actual magnitude of the increase in the Trunk Angle was small. The Peak Response of the Trunk Angle was in the anterior direction, whereas it was in the posterior direction for the CoP (regardless of the load timing condition).

Surprise Condition

Generally, the Peak Responses of the back muscles in the Surprise condition were lower compared to those in the T_K-F_{EF} and T_R-F_{EF} conditions. Perhaps because the sudden loading was truly unexpected in nature in the Surprise condition, it may have posed too great a risk to the extensors, especially given the presence of back and abdominal muscle fatigue in the F_{EF} condition. Therefore, instead of taking on the stress of the sudden load, the extensor muscles may have become less involved and have allowed other tissues or muscles of the body to absorb the shock. Or, perhaps the back muscles did not become more active because the abdominal muscles were impaired and, therefore, could not adequately react to maintain sufficient spine stability. Moreover, given the sudden, surprising nature of the perturbation, as well as the trunk muscle fatigue, a reaction from the trunk muscles may not have been enough, and so the leg muscles may have had to become more involved to maintain balance. These notions are supported by the mean Peak Response of the CoP, which was much higher in the Surprise

condition (-8.7 cm) than in the other two conditions ($T_K-F_{EF} = -4.5$ cm and $T_R-F_{EF} = -5.1$ cm). Therefore, a lesser response at the trunk may have occurred at the expense of a greater response in other muscles, as exhibited by the heightened change in the CoP.

Effect of Fatigue

Cocontraction

Increases in cocontraction may occur throughout the duration of fatigue, and not only immediately prior to an anticipated perturbation (in the Pre Response phase). Muscle fatigue can be viewed as a state of impairment. In order to protect the tissues of the body during this period of impairment, the body may increase the cocontraction of the fatigued muscles throughout the duration of fatigue, knowing that a perturbation may occur without notice. This perturbation need not take the form of sudden loading of the upper limbs. It may involve a slip of the feet while walking, accidentally dropping a weight, etc. In any event, the body is prepared due to the increased cocontraction during rest (at Baseline).

The current study is unique in that it incorporates abdominal fatigue in addition to back muscle fatigue. The addition of extensor fatigue led to an increase in the activity of not only the back muscles, but also of the abdominal muscles. Moreover, the addition of abdominal fatigue to the extensor fatigue led to a further increase in the muscle activity not only of the abdominal muscles, but also of the back muscles. These findings have important implications regarding spinal stability, and are evidence of increasing cocontraction of opposing muscle groups with fatigue. This held true even when only one of the muscle groups (the back muscles) became fatigued and *both* muscle groups increased their activity.

Furthermore, although it is obvious that the Baseline muscle activity increased as the degree of fatigue increased (from rested to extensor fatigue, and from extensor to flexor-extensor fatigue), there were no strategies of increased cocontraction employed just prior to the loading. Recall that, during sustained submaximal contractions, the EMG amplitude will increase in relation to the force that can be exerted (Petrofsky et al., 1982; Häkkinen & Komi, 1983; Kirsch & Rymer, 1987; Duchêne & Goubel, 1990). Essentially, fatigue decreases the efficiency of the muscle in transforming muscle excitation into muscle force (Bigland-Ritchie et al., 1979). This is likely the main reason why an increase in the Baseline activity was seen. In other words, a large portion of the increase in the muscle activity may have been due to the heightened effort that was required to stand in a stationary position while holding the bin.

However, it is also possible that a portion of this increase occurred due to other reasons. For instance, Potvin and O'Brien (1998) showed that when participants performed fatiguing lateral bend exertions, the EMG activity of the trunk muscles increased over and above the increase that would be expected solely due to the lowered efficiency of the muscle. Therefore, these authors deduced that fatigue led to an increase in the trunk muscle cocontraction forces.

The notion that this cocontraction is not only employed just prior to a known perturbation is supported by the means of the Surprise data in the current experiment. When viewing these means, the activation levels in the Pre Response phase were sometimes *larger* than they were in the other two load timing conditions (i.e., TES Surprise mean = 2.7, T_K-F_{EF} mean = 1.3, T_R-F_{EF} mean = 1.4), suggesting that increased cocontraction does not solely exist just prior to an expected, impending perturbation.

It is also possible that the increases in the muscle activity that occurred at Baseline were done to ensure that proper cocontraction (preparation) was made well in advance of the perturbation in the event a well-coordinated response could not be made just prior to the perturbation. It has been shown that fatigue leads to a decrease in the coordination of muscle contractions, and, consequently, to an increase in the use of unnatural muscle sequencing and movements (Mital et al., 1993; Potvin & O'Brien, 1998). Thus, with fatigue, the body may choose other (earlier) strategies to prepare for a perturbation rather than depending on the execution of a coordinated response just prior to a perturbation. This idea is also supported by the results of a previous study. Granata et al. (2001) reported that there was a significant increase in the preparatory trunk muscle activity with fatigue in situations of both expected loading and when there was no sudden loading. In their study, the data was averaged across the middle 3 s for the trials with no sudden loading, and across the 100 ms prior to load impact for the trials with the expected sudden loading.

Response Time

Moreover, an increase in pre-activation may also lead to a decreased reflexive latency following the perturbation. The increased pre-activation associated with fatigue may exist to compensate for the impaired state of these muscles by reducing the muscles' latency. This idea is supported in previous work by Allison and Henry (2002), which demonstrated that muscle latencies decrease with fatigue.

Although Häkkinen and Komi (1983) found that the latencies did not change with fatigue, they also found that the electromechanical delay increased with fatigue. The electromechanical delay exists because muscle activity must precede the mechanical force

output from the muscle. If the reaction time or muscle latency is equal to the time between stimulus onset and EMG onset, and if the electromechanical delay is equal to the time between EMG onset and force generation onset, then the TtPk measure used in the current experiment is really a combination of both latency and a portion of the electromechanical delay. Therefore, any increase in the electromechanical delay associated with fatigue (Häkkinen & Komi, 1983) may be compensated for by the decrease in muscle latency (Allison & Henry, 2002). Thus, any differences in these measures would have been washed out in the TtPk measure used in the current experiment.

Conclusions

For clarity, the conclusions will be presented in point form.

Effect of Load Timing

- Although, statistically speaking, there were APAs in the Trunk Angle and in the CoP just prior to anticipated sudden loading, the actual amplitudes of these APAs were quite small, likely due to the low impact of the sudden load.
- There was no significant increase in the trunk muscle cocontraction prior to loading, which is contrary to the findings of previous research (i.e., Thomas et al., 1998; Krajcarski et al., 1999; Stokes et al., 2000). Therefore, it is hypothesized that other segments of the body (namely the lower limbs) were preparing for the sudden load, especially given the presence of trunk muscle fatigue. The involvement of the lower limbs prior to anticipated perturbations have been observed in previous work

(Haumann, 2002; Brown et al., in press). In addition, the lack of significant increase in trunk muscle cocontraction may have been due to the low impact of the sudden load. The leg muscles in addition to the trunk muscles may have required a greater perturbation in order to elicit increased activation prior to anticipated loading.

- The Peak muscle responses and the CoP response following the perturbation were larger when the load timing was random than when the timing was known by the participant. This signifies that there must have been some preparation prior to the perturbation when the loading could be anticipated. If these preparations did not occur in the trunk segment, then they may have occurred in the lower limbs or even in the arms, as mentioned above.
- Increases in the Peak Responses of the antagonist (flexor) muscles were observed in the T_R condition, but these increases failed to reach significance. However, this trend may have been functionally important in terms of helping to stabilize the spine due to the increased extensor activity.
- The means from the Surprise trials suggest that, during very sudden, unexpected loading, the goal may be to protect the trunk muscles from tissue injury, as smaller Peak Responses were seen in the back muscles. The CoP Peak Response was much higher in the Surprise condition, however. This may indicate that muscles other than the trunk muscles were accepting the majority of the perturbation, thereby causing a greater change in the Peak CoP.

Effect of Fatigue

- Trunk muscle fatigue led to an increase in the Baseline activity of the trunk muscles but not in the activity just prior to loading. This suggests that there may have been increased spinal stiffness from the beginning of the loading trial (whenever the subjects were fatigued), and not just prior to the perturbation. This may be a protective mechanism of the body that serves to stiffen the spine in the event that a perturbation occurs during this impaired (fatigued) state.
- The increased abdominal activity with the addition of extensor fatigue, and the increased back muscle activity with the addition of flexor fatigue are evidence of increased cocontraction with muscle fatigue. This has important implications regarding spinal stability, as *both* muscle groups increased their activation even when only one of the muscle groups became fatigued.
- Fatigue had no effect on the Peak Responses of the trunk muscles, suggesting that the body successfully adapted to the fatigue prior to the perturbation. There was, however, a significant decrease in the Peak CoP Response from the F_0 to the F_{EF} conditions, although the magnitude of this difference was minor.
- The time it took for the variables to reach their peak was not altered with fatigue. However, this does not exclude the possibility that there were changes in the muscle onset latencies with fatigue, as has been shown previously (Allison & Henry, 2002).

Recommendations for Future Research

Given that several theoretical hypotheses have been presented in the current paper, there are many options for future research that would help to answer some of the questions posed here. For instance, other variables could be measured to help pinpoint where the changes were occurring. It is suggested that the integral of the curve following the perturbation be measured in addition to the Peak Response and the TtPk. For example, conditions may be very different in terms of their Peak Response and the time it took to get to that response, but when viewing the area under the curve, the net responses may be very similar. Also, better efforts should be made to determine the exact time of the load impact, such as placing a trigger in the bin that was held by the participant. From this data, muscle onset latencies can also be determined.

Moreover, because the trunk and legs work in concert in everyday living, more research should focus on examining the responses of the trunk and legs in concert. Also, perhaps the leg muscles could be fatigued (in the absence of trunk muscle fatigue) to determine if the body adapts differently than it does in the presence of trunk muscle fatigue. This is of special interest here, as it was proposed that the leg muscles may have taken on a larger role to prepare for the sudden perturbation, especially given the presence of trunk muscle fatigue. Furthermore, other muscles of the trunk can be examined. As indicated by McGill (2002), the quadratus lumborum, along with other muscles, play a major role in spinal stability. In addition, this study was unique in that it involved fatigue of opposing muscle groups. It would be interesting to further study the effects of only antagonist muscle fatigue on spinal stability.

It would also be interesting to study the effects of load timing and fatigue on clinical populations. Individuals who suffer from back pain, for example, may prepare for and react differently to a perturbation compared to healthy individuals. Similar to muscle fatigue, back pain can be viewed as a state of impairment of the body, both in the chronic and in the acute sense.

Finally, other methods of perturbation can be imposed on individuals. The current experiment employed a quasi-static sudden loading method, but it would be interesting to study the changes that occur during rapid unloading or during a dynamic lifting task that is typically experienced in the workplace environment.

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APPENDIX A

Data Collection Information and Consent Form

RESEARCH PROJECT TITLE

The Effects of Trunk Muscle Fatigue and Load Timing on the Anticipatory and Reactive Changes During Sudden Hand Loading

RESEARCHERS AND INSTITUTION

1. Diane Grondin, Graduate Student, Faculty of Human Kinetics, University of Windsor (253-3000 x2468; Room 221 HK Building; di_13fly@hotmail.com)
2. Dr. Jim Potvin, Associate Professor, Faculty of Human Kinetics, University of Windsor (253-3000 x2461; Room 117 HK Building; jpotvin@uwindsor.ca)

PURPOSE OF STUDY

The purpose of this study is to examine the control of spine mechanics in response to midsagittal plane loading of the hands, as it applies to trunk stability. The effects of trunk muscle fatigue will be investigated in combination with knowledge of load timing.

METHODS

Participants will be asked to maintain an upright posture with their arms slightly outstretched, while comfortably holding a bin in their hands. The participant will not be able to see the bin, which will be placed behind a black curtain hanging down to the level of the participant's forearms. A combination of five loading conditions will be used: Three levels of Fatigue (rested, low back fatigue, and concurrent low back and abdominal fatigue), and two levels of Load Timing (known and random). The load will be applied in the midsagittal plane, into the bin held by the participant. In the known timing condition, the participant will be verbally cued of the loading via a countdown conducted by the experimenter. In the random timing condition, the subject will receive no verbal cues of the impending load. The actual application of the load onset will be varied from 2 to 10 seconds. In the rested condition, participants will be fully rested, whereas in the low back fatigue condition, subjects will have performed a series of isometric static contractions to fatigue the back extensors prior to the test trials. Similarly, for the concurrent low back and abdominal fatigue, subjects will perform a series of back and abdominal contractions so that both are fatigued before testing. The load magnitude will be equal to 5.0 kg.

Electromyography (EMG) will be collected from four muscles on the right side of the body (lumbar erector spinae, thoracic erector spinae, external oblique, and internal oblique) to measure the trunk muscle activity just prior to, and following, the sudden loading. Centre of pressure data will also be collected from the force platform on which the subjects will stand, and trunk displacement data will be collected by attaching a goniometer to the lumbar spine. Prior to the test trials, maximum voluntary contractions (MVCs) will be collected from each muscle group.

DESCRIPTION OF RISKS

The induced perturbation is sudden but not ballistic in nature. It is not designed to be strenuous for the subject. However, participants may experience some muscle stiffness after the collection. Sudden, unexpected loadings, similar to those outlined here, have been performed in previous work (Marras et al., 1987; Lavender et al., 1989; Lavender & Marras, 1995) and in conjunction with back muscle fatigue (Parcero, 2000; Granata et al., 2001). Subjects should do some stretches following the collection session in order to minimize any muscle stiffness. Furthermore, the MVCs and the fatiguing intervals will be made under very safe conditions, with secure restraints and with confirmation that the subject is only supposed to contract to levels that she feels are safe for her.

In addition, the self-adhesive, surface electrodes for EMG collection may cause a slight skin irritation. This discoloration will not last longer than a day or two and poses no risk to the participant.

CONFIDENTIALITY

All data will be kept confidential. Only the researchers mentioned above will know your identity and personal information. This information will be stored in a secure computer in the Ergonomics or Biomechanics Laboratory and will not be discussed or displayed in any form that would provide an indication of your identity.

FEEDBACK

The procedures and methods pertaining to this study will be communicated both verbally and in written format prior to the onset of the study. If there has been anything neglected or something you wish to be further clarified, feel free to ask questions at any time before, during, or after the study. If desired, subjects will be given verbal and/or written feedback once all the data has been analyzed.

REMUNERATION

You will receive \$30.00 for participating in this study.

RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. This study has been reviewed and received ethics clearance through the University of Windsor Research Ethics Board. If you have questions regarding your rights as a research subject, contact:

Research Ethics Co-ordinator
University of Windsor
Windsor, ON
N9B 3P4

Telephone: (519) 253-3000 x3916
E-mail: ethics@uwindsor.ca

SIGNATURE OF RESEARCH SUBJECT/LEGAL REPRESENTATIVE

I understand the information provided for the study "The Effects of Trunk Muscle Fatigue and Load Timing on the Anticipatory and Reactive Changes During Sudden Hand Loading", as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study.

Name of Subject

Signature of Subject & Date

SIGNATURE OF INVESTIGATOR

In my judgment, the subject is voluntarily and knowingly giving informed consent to participate in this research study.

Signature of Investigator & Date

APPENDIX B

The means and standard deviations of the percent decline in the MPF for the back muscles (TES and LES) during the different back fatiguing intervals (n = 15).

	TES				LES			
	Ext fat interval 1	Ext fat interval 2	Ext fat interval 3	Ext fat interval 4	Ext fat interval 1	Ext fat interval 2	Ext fat interval 3	Ext fat interval 4
Subject 1	10	15	21	14	27	33	28	21
Subject 2	28	24	37	19	50	22	45	17
Subject 3	25	26	25	21	39	33	33	25
Subject 4	N/A	17	12	12	N/A	38	25	13
Subject 5	18	20	6	6	22	20	19	8
Subject 6	29	13	20	17	46	33	21	27
Subject 7	2	15	19	24	10	29	19	23
Subject 8	18	17	20	17	22	23	19	22
Subject 9	26	28	28	26	30	36	45	38
Subject 10	5	19	6	3	23	20	20	3
Subject 11	11	4	15	12	24	13	24	18
Subject 12	10	25	28	31	2	36	34	33
Subject 13	11	24	5	14	10	24	15	23
Subject 14	17	9	2	12	23	13	16	15
Subject 15	24	22	16	24	23	21	22	25
Mean	17	19	17	17	25	26	26	21
SD	9	7	10	8	13	8	10	9

The means and standard deviations of the percent decline in the MPF for the abdominal muscles (EO and IO) during the different abdominal fatiguing intervals (n = 15).

	EO		IO	
	Ab fat interval 1	Ab fat interval 2	Ab fat interval 1	Ab fat interval 2
Subject 1	23	12	-84	-44
Subject 2	15	23	31	22
Subject 3	42	8	-42	-7
Subject 4	2	38	4	-4
Subject 5	12	25	4	19
Subject 6	10	31	-1	26
Subject 7	18	16	6	4
Subject 8	-1	21	-8	15
Subject 9	28	16	-18	2
Subject 10	23	0	9	6
Subject 11	19	-7	16	-45
Subject 12	9	14	-20	12
Subject 13	15	13	28	-13
Subject 14	23	11	9	14
Subject 15	23	5	21	8
Mean	17	15	-3	1
SD	11	12	29	21

APPENDIX C

The means and standard errors across all fatigue levels (n = 15).

		Means			Standard Errors		
		F _O	F _E	F _{EF}	F _O	F _E	F _{EF}
TES	Baseline	4.8	5.6	6.5	0.5	0.5	0.6
	Pre Response	2.5	1.8	1.3	0.9	0.2	0.3
	Peak Response	15.7	16.6	15.8	1.2	1.2	0.9
	TtPk Response (ms)	176	178	180	6	5	5
LES	Baseline	4.1	4.8	4.6	0.3	0.4	0.4
	Pre Response	1.2	1.3	1.1	0.1	0.2	0.2
	Peak Response	11.2	11.8	11.7	0.7	0.7	0.8
	TtPk Response (ms)	182	188	183	9	6	7
EO	Baseline	4.7	5.5	5.6	0.6	0.7	0.7
	Pre Response	0.5	0.5	0.3	0.1	0.1	0.2
	Peak Response	5.6	5.6	5.1	0.6	0.6	0.5
	TtPk Response (ms)	151	129	138	14	13	14
IO	Baseline	5.1	5.6	6.1	0.6	0.6	0.7
	Pre Response	0.7	0.7	0.9	0.1	0.1	0.2
	Peak Response	6.6	5.9	6.7	0.7	0.7	0.9
	TtPk Response (ms)	204	201	189	7	8	9
CoP (cm)	Baseline	2.3	1.5	2.4	1.0	1.2	1.1
	Pre Response	-0.1	-0.1	-0.1	0.0	0.0	0.0
	Peak Response	-5.1	-4.9	-4.8	0.1	0.1	0.1
	TtPk Response (ms)	505	507	493	14	11	11
Trunk Ang (degrees)	Baseline	-5.3	-4.6	-3.9	1.3	1.7	2.2
	Pre Response	0.0	0.1	0.1	0.0	0.0	0.0
	Peak Response	6.3	5.8	5.6	0.5	0.4	0.5
	TtPk Response (ms)	437	429	445	11	12	21

The means and standard errors across both load timing levels ($n = 15$).

		Means		Standard Errors	
		T_K	T_R	T_K	T_R
TES	Baseline	5.7	5.5	0.5	0.4
	Pre Response	1.7	2.0	0.2	0.6
	Peak Response	15.3	16.8	0.8	1.0
	TtPk Response (ms)	170	185	4	4
LES	Baseline	4.4	4.6	0.3	0.3
	Pre Response	1.3	1.2	0.1	0.1
	Peak Response	11.1	12.1	0.6	0.6
	TtPk Response (ms)	176	193	5	6
EO	Baseline	5.3	5.3	0.6	0.5
	Pre Response	0.4	0.5	0.1	0.1
	Peak Response	5.4	5.5	0.4	0.5
	TtPk Response (ms)	138	141	11	12
IO	Baseline	5.6	5.6	0.5	0.5
	Pre Response	0.8	0.6	0.1	0.1
	Peak Response	6.2	6.5	0.6	0.6
	TtPk Response (ms)	193	202	7	6
CoP (cm)	Baseline	2.1	2.0	0.9	0.8
	Pre Response	-0.1	0.0	0.0	0.0
	Peak Response	-4.6	-5.2	0.1	0.1
	TtPk Response (ms)	532	479	9	9
Trunk Ang (degrees)	Baseline	-4.7	-4.7	1.6	1.2
	Pre Response	0.1	0.0	0.0	0.0
	Peak Response	5.2	6.7	0.3	0.4
	TtPk Response (ms)	433	440	11	13

APPENDIX D

The means and standard deviations for the Surprise condition (n = 13).

		Mean	SD
TES	Baseline	5.3	2.7
	Pre Response	2.7	3.5
	Peak Response	14.0	6.7
	TtPk Response (ms)	177	74
LES	Baseline	5.6	7.4
	Pre Response	1.3	1.7
	Peak Response	11.0	4.0
	TtPk Response (ms)	208	72
EO	Baseline	7.5	11.0
	Pre Response	0.2	3.7
	Peak Response	5.5	5.0
	TtPk Response (ms)	191	131
IO	Baseline	5.6	2.6
	Pre Response	1.4	1.7
	Peak Response	4.9	3.8
	TtPk Response (ms)	206	56
CoP (cm)	Baseline	3.0	6.4
	Pre Response	0.0	0.4
	Peak Response	-8.7	5.9
	TtPk Response (ms)	492	136
Trunk Ang (degrees)	Baseline	-5.5	87.7
	Pre Response	0.0	0.2
	Peak Response	5.7	3.8
	TtPk Response (ms)	408	233

The means for the Surprise condition ($n = 13$) compared to the means for the T_K-F_{EF} and T_R-F_{EF} conditions ($n = 15$). Means are presented only for the variables where a significant effect of *Load Timing* was found.

		TK	TR	Surprise
TES	Baseline	—	—	—
	Pre Response	—	—	—
	Peak Response	15.0	16.6	14.0
	TtPk Response (ms)	—	—	—
LES	Baseline	—	—	—
	Pre Response	—	—	—
	Peak Response	10.8	12.6	11.0
	TtPk Response (ms)	172	195	208
EO	Baseline	—	—	—
	Pre Response	—	—	—
	Peak Response	—	—	—
	TtPk Response (ms)	—	—	—
IO	Baseline	—	—	—
	Pre Response	—	—	—
	Peak Response	—	—	—
	TtPk Response (ms)	—	—	—
CoP (cm)	Baseline	—	—	—
	Pre Response	-0.2	0.0	0.0
	Peak Response	-4.5	-5.1	-8.7
	TtPk Response (ms)	506	479	492
Trunk Ang (degrees)	Baseline	—	—	—
	Pre Response	0.2	0.0	0.0
	Peak Response	5.2	6.0	5.7
	TtPk Response (ms)	—	—	—

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